DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

CECW-ED

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Technical Letter
No. 1110-2-365

31 August 1994

Engineering and Design
NONLINEAR, INCREMENTAL STRUCTURAL ANALYSIS OF MASSIVE CONCRETE STRUCTURES

Distribution Restriction Statement

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1. Purpose

This engineer technical letter (ETL) provides guidance for performing a nonlinear, incremental structural analysis (NISA) for massive concrete structures (MCS).

2. Applicability

This ETL applies to HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities (FOA) having responsibilities for the design of civil works projects.

3. References

a. EM 1110-2-2000, Standard Practice for Concrete.

b. ACI Committee 207. 1973 (Reapproved 1986). "Effect of Restraint, Volume Change, and Reinforcement on Cracking of Massive Concrete," ACI 207.2R-73, American Concrete Institute, Box 19150, Detroit, MI 48219.

c. ANATECH Research Corp. 1992. "ANACAP-U, ANATECH Concrete Analysis Package, Version 92-2.2, User's Manual," P. O. Box 9165, Ladolla, CA 92038.

d. Garner, S. B., Bombich, A. A., Norman, C. D., Merrill, C., Fehl, B., and Jones, H. W. 1992. "Nonlinear, Incremental Structural Analysis of Olmsted Locks and Dams - Volume I, Main Text," Technical Report SL-92-28, U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

e. Hibbitt, Karlsson, and Sorenson, Inc. 1989. "ABAQUS User's Manual, Version 4.9," Pawtucket, RI 02860.

4. Discussion

a. Background. Current design practice for MCS was developed in the 1960's. Structural analysis methods did not integrate the effects of thermal and mechanical stresses and did not accurately predict the behavior of complex hydraulic structures. Results were usually safe, but very conservative. Advances in analysis techniques and computer technology have greatly improved structural design capabilities. Finite element analysis can be used to account for complex geometry and loading, thermal stresses, nonlinear material behavior, and sequential construction. These techniques have already been applied to the design of lock monoliths, arch dams, and other MCS. They provide a more realistic, comprehensive understanding of structural behavior.

b. Types of massive concrete structures. MCS are defined by the American Concrete Institute Committee 207 (1973-R86) as "any large volume of cast-in-place concrete with dimensions large enough to require that measures be taken to cope with the generation of heat and attendant volume changes to minimize cracking." There are three types of MCS commonly used for civil works projects. Gravity structures are used for dams and lock walls; thick shell structures are used for arch dams; and thick

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reinforced plates are used for U-frame locks, large pump stations, and powerhouses.

5. Criteria

a. Design guidance. NISA should be used as a supplemental tool for the design of MCS. The MCS must also satisfy applicable criteria contained in other guidance documents. When a NISA is needed to achieve any of the listed objectives presented in paragraph 5*b*, it should be performed per the guidance in Appendix A. This guidance has been developed from design experience on several recent civil works projects. Examples of such designs are provided by Garner, et al. (1992). Excerpts from this reference are included in Appendix B.

b. Objectives. NISA of MCS should be used when it is necessary and cost effective to achieve one or more of the following design objectives.

(1) To develop structures with *improved performance* where existing similar structures have exhibited extensive cracking during construction or operation. This objective is to limit cracking to minor occurrences in noncritical areas. It is neither necessary nor realistic to completely eliminate cracking.

(2) To more accurately *predict behavior of unprecedented structures* for which limited experience is available; for example, those with unusual structural configuration, extreme loadings, unusual construction constraints, or severe operational requirements.

(3) To provide *cost savings* by revising the structural configuration, material requirements, or construction parameters.

c. Action.

(1) The need to perform a NISA should be identified during the Feasibility Phase of project development. Necessary design studies and resources should be included in the Project Management Plan. Proper identification of objectives is the key to determining the required scope of studies. Contact CECW-ED for assistance in determining appropriate levels of investigation and the necessary resources.

(2) Structural engineers should perform a NISA during the early stages of design. This will enable the design team to use NISA results to make key design decisions at appropriate times. Usually the analysis will occur during the initial stages of preconstruction engineering and design (PED). However, if an unprecedented structural configuration is being proposed, it may be necessary to perform a NISA during the feasibility phase to identify requirements for design changes and unusual construction procedures which will significantly affect project costs. Guidance for performing a NISA during the feasibility phase is contained in Annex 1 of Appendix A.

(3) A NISA should be based on test results of the proposed concrete mixture for the project. Therefore, when a NISA is expected, it is critical to conduct concrete materials tests at the earliest possible time. The structural engineer must communicate this requirement to the materials engineer, since normal thermal studies required by EM 1110-2-2000 may be conducted later in the design process. If test results are delayed excessively, it may be necessary to initiate the NISA without the test data. If this undesirable situation occurs, properties should be selected as described in Annex 1, Appendix A, for a NISA during the feasibility phase. Once testing is completed, the performance of the NISA during the feasibility phase must be verified with NISA's using the material properties from the test results.

(4) The structural engineer is primarily responsible for performing the NISA. However, adequate analysis and evaluation of design alternatives require participation of a design team including structural, materials, geotechnical, cost, and construction engineers. This team must ensure that NISA results are properly incorporated into the overall design of the MCS. Proper coordination is required for: selection of concrete properties, foundation properties, and construction parameters; refinement of the analysis through changes in structural configuration or construction parameters, or revised material data for concrete or foundation; economic evaluation of design alternatives.

(5) Due to the fact that NISA is a state-of-the-art procedure and there are many complex issues associated with performing a NISA, periodic review meetings should be held throughout the performance of a NISA study to ensure that the plan of action

being pursued is acceptable to all elements involved. Representatives from CECW-ED and CECW-EG and their counterparts from the division office reviewing the project documents should be present at these meetings.

(6) Actual construction conditions may not match the assumed conditions used for the NISA. When this occurs, the team should evaluate the altered conditions and determine the need to revise the design or conduct additional NISA studies.

d. Documentation. Results of the NISA should be documented in a separate design memorandum entitled "Nonlinear, Incremental Structural Analysis." Required report content is identified in Appendix A.

e. Deviations. Any deviation from specific requirements of the enclosed guidance requires consultation with and the approval of CECW-ED. Such approval should be obtained in advance of the analysis. Approval is required for actions such as deletion of required parameter combinations, use of narrow bandwidths without material property tests, or use of a computer code other than ABAQUS (Hibbitt, Karlsson, and Sorenson 1989) with the ANACAP-U subroutine (ANATECH Research Corp. 1992).

FOR THE DIRECTOR OF CIVIL WORKS:

2 Appendices
APP A - Nonlinear, Incremental Structural Analysis (NISA) of Massive Concrete Structures
APP B - Examples

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APPENDIX A: NONLINEAR, INCREMENTAL STRUCTURAL ANALYSIS (NISA) OF MASSIVE CONCRETE STRUCTURES

A-1. Introduction

a. Purpose. Massive Concrete Structures (MCS) are constructed using the principles and methods defined for mass concrete by American Concrete Institute (ACI) Committee 207 (ACI 1992a and b) and EM 1110-2-2000, Standard Practice for Concrete. MCS should be analyzed in accordance with the guidance contained within this appendix during the preconstruction engineering and design (PED) phase of the project. Should the performance of a NISA study become necessary during the feasibility phase of a project, it should be accomplished in accordance with Annex 1 of this appendix. There are three types of MCS commonly used for civil works projects. Gravity structures are used for dams and lock walls; thick shell structures are used for arch dams; and thick, reinforced plate structures are used for U-frame locks, large pump stations, and powerhouses. Thick reinforced plate members are unique from typical concrete structures because the horizontal flexural members are placed in multiple lifts, and most members are lightly reinforced (i.e., reinforcement ratios less than 1 percent). For any of the aforementioned MCS, it may be necessary to perform a nonlinear, incremental structural analysis. A NISA should account for the complex geometry of the structure, the nonlinear behavior of plain or reinforced concrete members, the interaction of the structure, foundation, and backfill, and the effects of sequential construction, thermal gradients, and surface and gravity forces. A NISA may be necessary and cost effective to attain any of the following design objectives:

(1) To develop structures with improved performance where existing similar structures have exhibited unsatisfactory behavior (such as extensive cracking) during construction or operation. Cracking which requires remedial repairs would be considered unsatisfactory behavior. Cracking which does not affect the overall structural behavior or some function of the structure would not be classified as unsatisfactory behavior.

(2) To more accurately predict behavior of unprecedented structures for which limited experience is available; e.g., those with unusual structural configuration, extreme loadings, unusual construction constraints, or severe operational requirements.

(3) To provide cost savings by revising the structural configuration, material requirements, or construction sequence. Cost savings may be achieved through items such as increased placing temperatures, increased lift heights, and reduced insulation requirements.

b. Project design process. A NISA should be performed as early in the design process as possible, but it is preferable that the actual performance of a NISA not take place until test data are available which will typically occur during the PED phase. A NISA should be performed during the feasibility phase only for unprecedented structures and/or those with requirements for unusual construction procedures and when it has been determined that these factors will significantly affect project costs. A NISA during the feasibility phase is primarily to provide insight and information as to whether or not construction of the structure is viable. If a NISA is performed during the feasibility phase, then this analysis should be verified for accuracy once test data from the project are available.

(1) Planning. During the feasibility phase of project design, the need to perform a NISA should be evaluated, based on the objectives stated above. Any potential construction savings, historical problems related to structural behavior, or special unprecedented structural features should be identified. Proposed solutions requiring NISA should be presented, and the necessary design studies along with their associated costs and schedule should be included in the Project Management Plan as described in ER 1110-2-1150.

(2) Initial NISA. The initial investigations needed to verify the potential cost savings, functional improvements, or predicted behavior should be performed in the early stages of the PED. NISA's should include project specific material properties based on test data. Initial analyses should be used to investigate typical two-dimensional (2-D) monoliths. These analyses should be used to evaluate the need for changes in monolith design, material properties, or construction parameters. These initial analyses

will be used to develop the final design parameters to be used in evaluating the various monoliths.

(3) Final NISA. A final NISA should be completed late in the design process, using the design parameters selected in the initial NISA to verify the selected designs. The analysis should be based on the final design layout and the parametric combination which produced the worst condition in the initial NISA studies. Should actual conditions during construction deviate from those assumed for the final analysis, it may be necessary to perform another NISA using the actual field conditions.

c. NISA process. The NISA process is basically composed of a heat transfer analysis and a stress analysis. The heat transfer analysis is performed to determine how the temperatures within the structure change with time. The stress analysis is performed to determine the stress and strain state of the structure based on these changing temperatures, gravity loads, changing material properties, and the boundary conditions. A description of these two types of analyses is provided in the following paragraphs. Parametric studies are an important part of performing a NISA and are used to assist the engineer in making the proper decisions for design and construction parameters. Use of parametric studies is discussed in paragraph A-2*g*. Once analyses are completed, it is necessary to evaluate the results as described in paragraph A-6 to determine the effects of various parameters. Finally, the results, conclusions, recommendations, and any cost savings should be reported as described in paragraph A-7.

(1) General. To date, NISA's have been performed using the finite element (FE) code ABAQUS (Hibbitt, Karlsson, and Sorensen 1989). Since experience has been gained by using ABAQUS and its associated user supplied subroutines (UMAT, DFLUX, and HETVAL), discussion will be based on the methods used by ABAQUS for performing a NISA as well as these user supplied subroutines used by ABAQUS.

(2) Heat transfer analysis. A flow chart defining the steps in a heat transfer analysis is presented in Figure A-1. The first step is the basic step necessary for any FE analysis in which the structure and foundation are discretized into a group of elements defined by nodes. Once the nodes and elements have been defined, it is necessary to define node and element sets for items such as material properties, initial conditions, and film coefficients. The material properties must then be defined and should include the conductivity, density, and specific heat of any materials used in the analysis. This will require properties for both the concrete and foundation and possibly air. The initial temperature of the concrete must be defined and is typically assumed to be the placing temperature. A definition of the air temperatures should be made as described in paragraph A-2*c*. Finally, a definition of the time history must be made as shown in steps 6 and 7 of Figure A-1. This includes defining the length of each step and its increment, changing the model as necessary, applying, removing, and changing film coefficients as required, applying the heat generation (paragraph A-5*a*(2)), and defining any required output. It is critical that a temperature output file be defined properly to ensure that temperatures needed for the stress analysis are computed properly.

(3) Stress analysis. A flow chart defining the steps in a stress analysis is presented in Figure A-2. The node and element data defined in the heat transfer analysis for the concrete are typically used in the stress analysis and these data can then be used to identify the needed node and element sets. Input parameters for the user material subroutine must be determined by calibrating the model for the concrete mixture being analyzed with the test results for that mixture. If springs are used in place of continuum elements to model the foundation, then spring constants must be determined and used as a definition of the spring properties. A definition of the initial boundary conditions must be specified prior to beginning a time-history analysis. As in the heat transfer analysis, the final process in the stress analysis is to define the time-history analysis to take place as shown in steps 6 and 7 of Figure A-2. This includes defining the time of the steps and their increments, defining changes in the model, application of mechanical loads, accessing the temperature data from the heat transfer analysis to define thermal loads, and definition of the output desired.

d. Coordination. A design team consisting of structural, materials, geotechnical, cost, and construction engineers should be established prior to performing a NISA study. Interdisciplinary coordination is essential to ensure that the complex structural analysis is based on reliable concrete and foundation properties and realistic construction techniques. The structural, materials, and construction engineers should predict an appropriate set of construction conditions

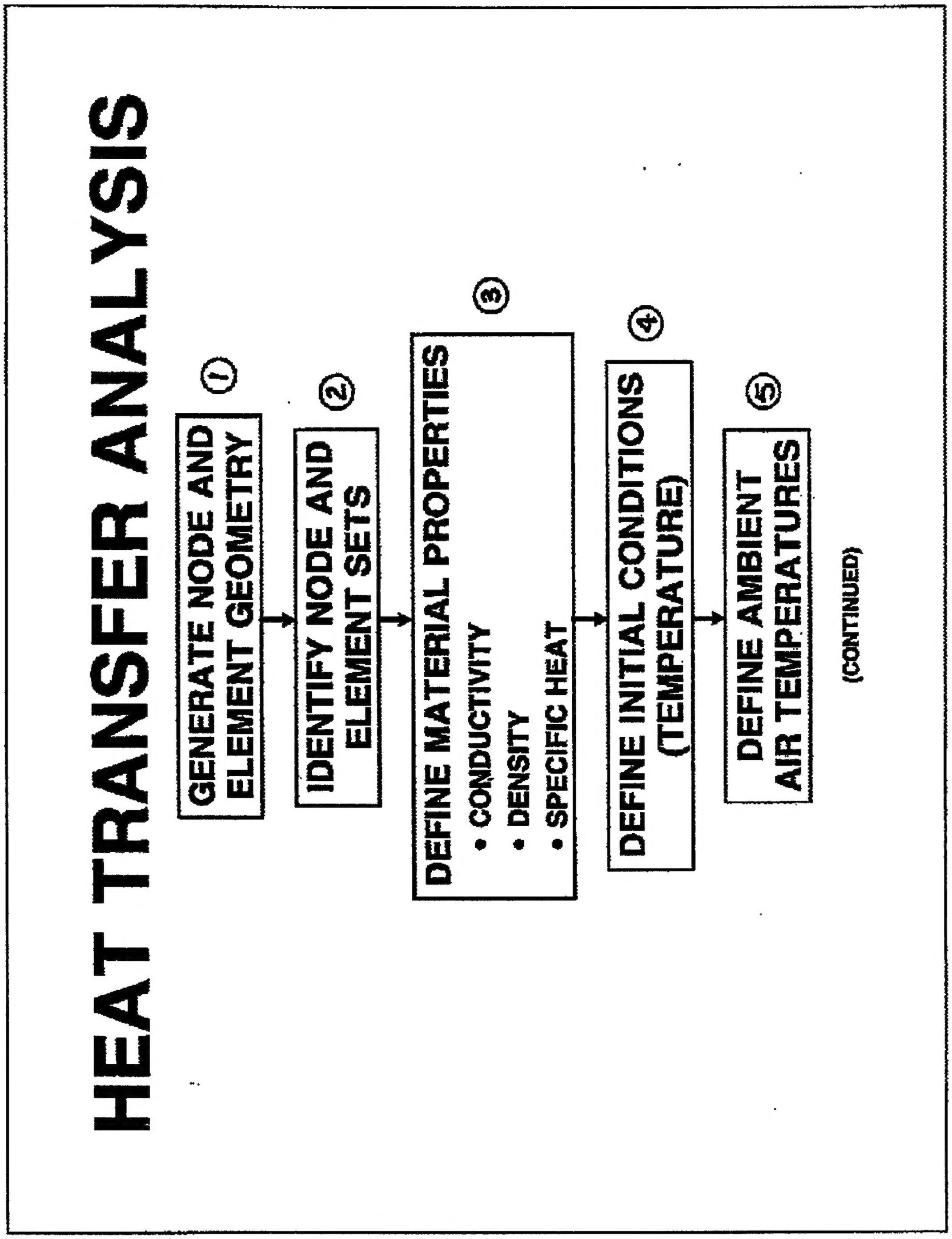

Figure A-1. Steps to be performed in the heat transfer analysis portion of a NISA (Continued)

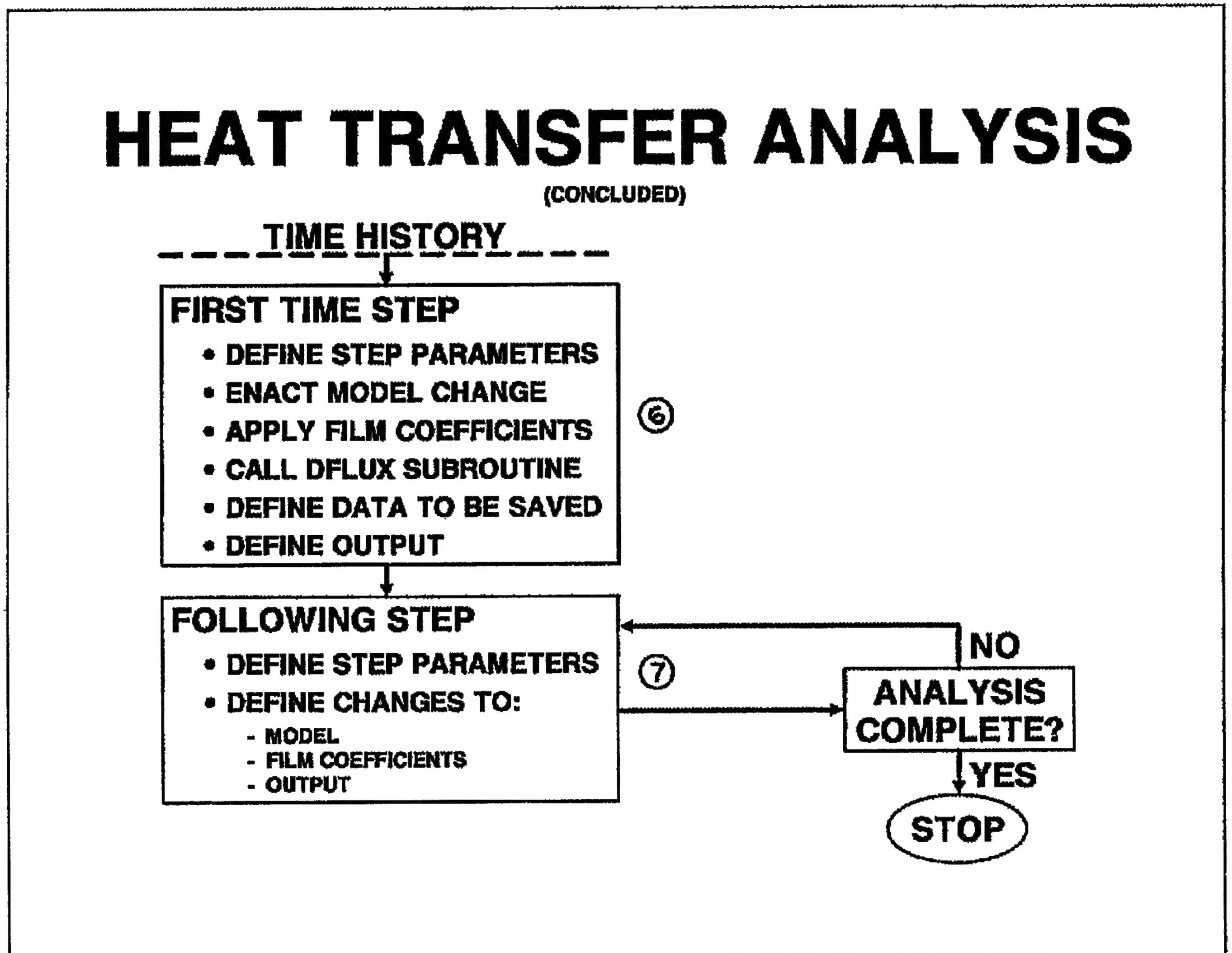

Figure A-1. (Concluded)

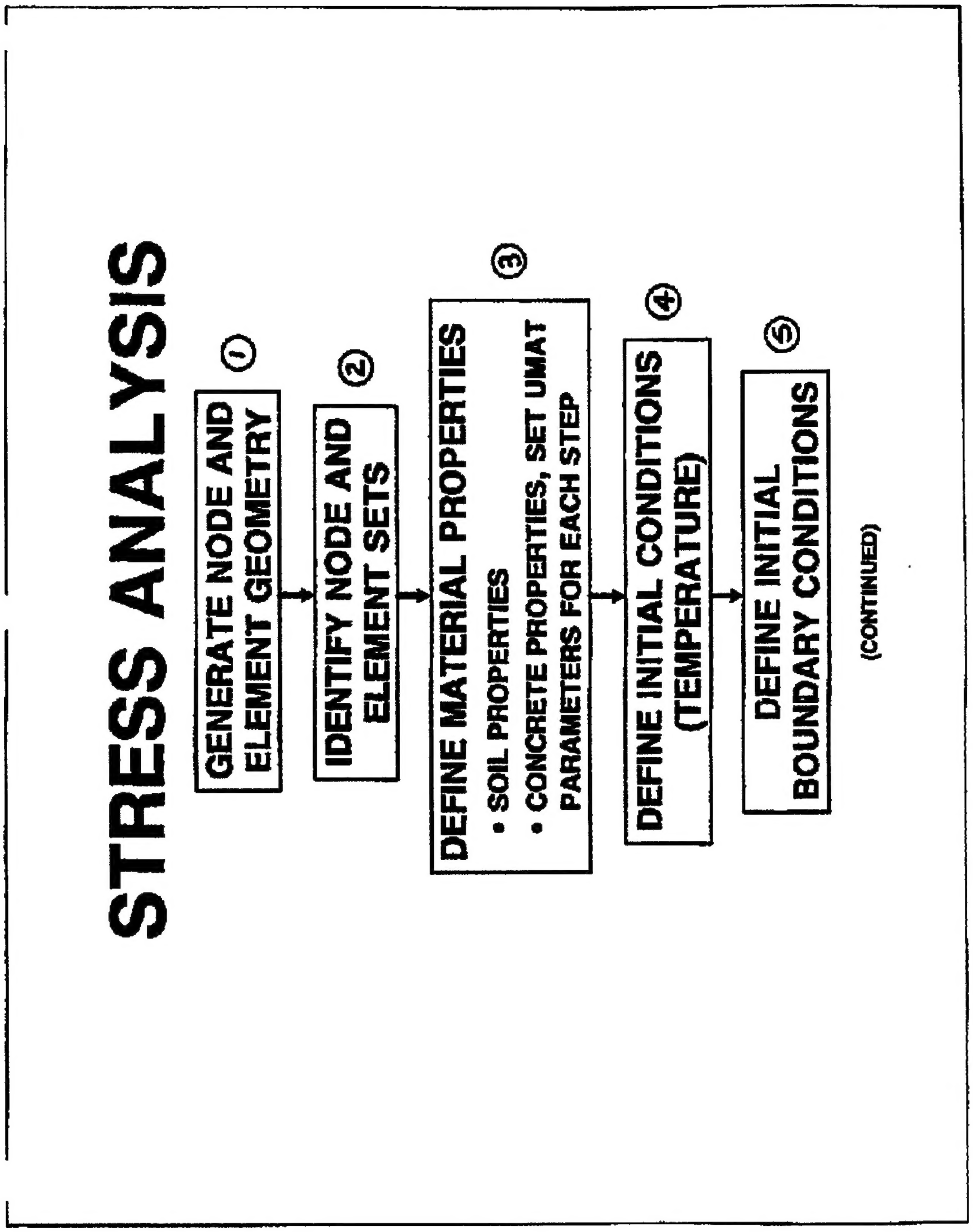

Figure A-2. Steps to be performed in the stress analysis portion of a NISA (Continued)

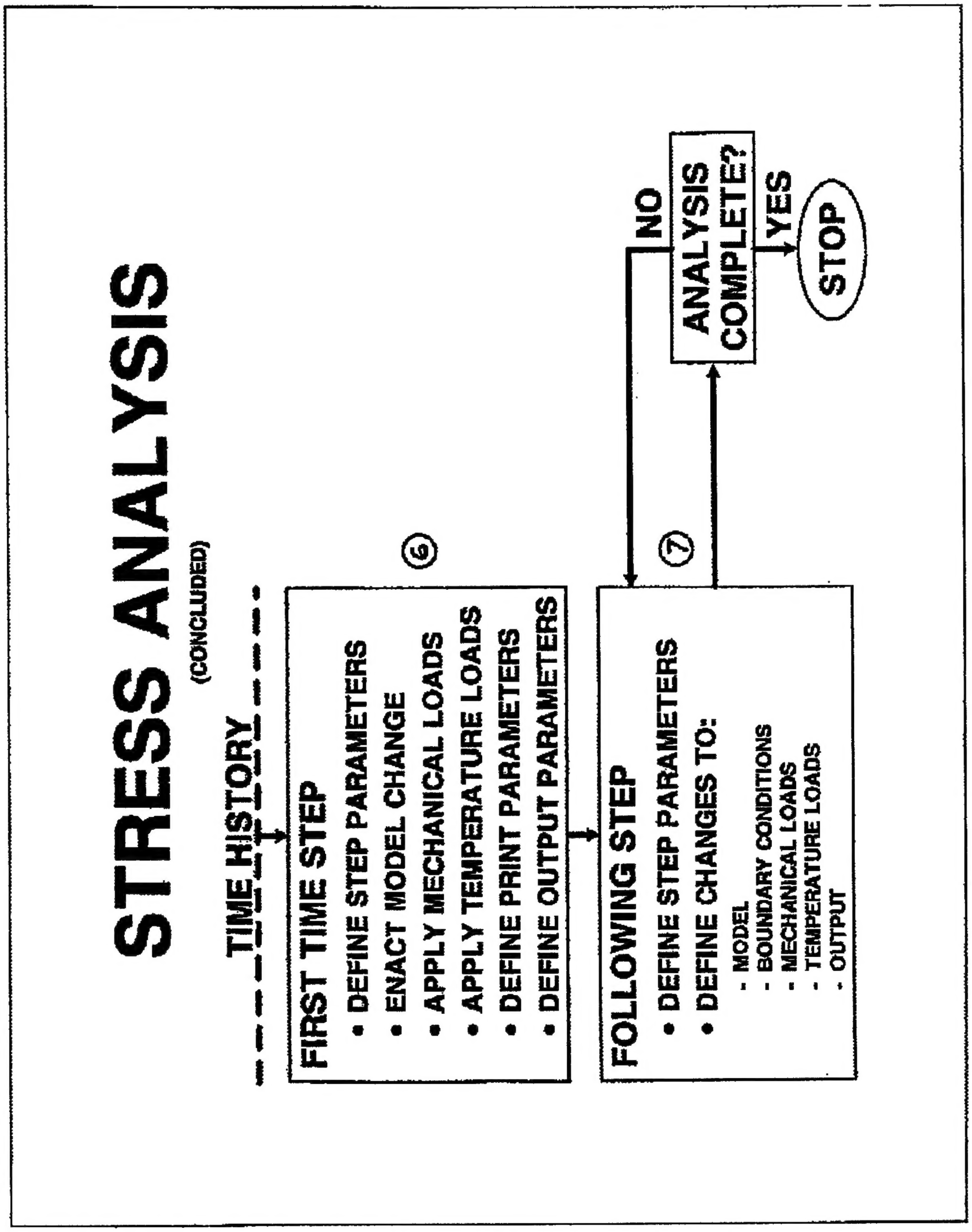

Figure A-2. (Concluded)

(e.g., time between lifts, lift heights, type of formwork, formwork removal, construction start date, insulation requirements, etc.) which will approximate actual field conditions and which can be adequately modeled. The materials engineer and structural engineer should develop a set of time-dependent curves to be used in the analytical model for the aging modulus, adiabatic temperature rise, creep, and shrinkage based on the results of laboratory testing. These curves will be banded to reflect the typical variations specified in paragraph A-2*b*(2) and the confidence level the materials engineer has with the local site conditions. Other concrete properties (e.g., tensile strain capacity, the coefficient of thermal expansion, thermal conductivity, specific heat, density, and Poisson's ratio) should be provided for the proposed concrete mixtures by the materials engineer through results of test data. The geotechnical engineer and structural engineer should develop appropriate values for the thermal conductivity, coefficient of thermal expansion, specific heat, density, and Poisson's ratio for the foundation material, and the pile-subgrade reaction moduli. The structural engineer should obtain the monthly average ambient air temperatures as described in paragraph A-2*c*. It will be the structural engineer's responsibility to ensure that the specified parameters are properly modeled for the numerical analysis. When modeling assumptions must be made, the structural engineer should consult with other design team members as necessary, but the final decision on how to implement the various parameters will be made by the structural engineer.

e. Assumptions, simplifications, and limitations. This guidance is based on proven methods of FE analysis, on NISA's performed on Corps of Engineers projects, and from independent parametric studies. The past experience has highlighted the following points.

(1) Variations in input data. The analysis requires reliable, but not exact, input data for meaningful results. Since exact data are not available, parametric studies are valuable in predicting the trends in behavior that can be expected in a given structure.

(a) Material properties. Variations in material properties due to scatter of test data, differences in behavior of the material between actual and that predicted by the numerical model, and expected differences between the laboratory mixture and the actual mixture used during construction can be accounted for by performing parametric studies using combinations of the upper and lower bounds described in paragraph A-2*b*.

(b) Start times. Variations in behavior will occur due to construction of a monolith beginning at different times of the year and these variations should be accounted for. Assuming construction starts at different times of the year may identify additional critical areas of the structure. Minimum requirements for analyses with different start times are presented in paragraph A-2*d*.

(c) General. Variations in other parameters may also be accounted for by varying the parameter of interest while other parameters remain constant. General guidance on performing a parametric study is given in paragraph A-2*g*. This approach can be used to identify and confirm cost-saving construction techniques and to increase the structural designer's confidence in the results that are being produced. For cases when cracking appears to be imminent for a given set of conditions and the variation of some other parameter could induce crack initiation, a parametric study may be valuable in assessing the designer's confidence in the satisfactory behavior of the structure.

(2) Methods of analysis. Two-dimensional NISA's of entire monolith cross sections are currently practical. Three-dimensional (3-D) NISA's are typically performed on isolated portions of structures, or sometimes entire monoliths may be modeled, primarily to determine the 3-D behavior of the structure in all directions. Three-dimensional NISA's may also be used to confirm 2-D results. Most structures should be modeled using a plane-stress approach. Plane-strain modeling may also be considered, but studies have shown that differences between the plane stress and plane strain approach are minimal for the results in the plane being evaluated (Truman, Petruska, and Ferhi 1992 and Garner et al. 1992). The selection of an appropriate approach is a matter of engineering judgment with consideration given to factors such as the volumetric change which may occur in the out-of-plane direction, the ability of the ends of the monolith to move with respect to each other, and the length of the monolith. For example, if volume changes are small, the selection between plane stress and plane strain will create little difference in the results, but if these volumetric changes are large the length of the monolith may be the determining factor for which model to use. The longer a

monolith is, the closer a typical strip near the center of the monolith will approach the plane-strain condition. If substantial out-of-plane loadings exist, then behavior due to these loads should be thoroughly investigated through the use of 2-D strips taken in the out-of-plane direction or by performing a 3-D analysis.

(3) Constitutive relations. A NISA includes constantly changing material properties which means that from one time increment to the next the properties of the material are different. The properties include nonlinear behavior such as creep. This precludes the use of superposition. The change in strain from one step to the next is used in the calculation of the new stress state as well as updating the constitutive matrix which is used in computing the displacements in the following time increment. This differs from a conventional linear elastic analysis where the constitutive matrix remains constant throughout the analysis.

(4) Drying shrinkage. Because most NISA's use moderately large element sizes and because in a NISA shrinkage can be treated only at the FE integration points, the effects of drying shrinkage near the surface of the structure are neglected. However, drying shrinkage is typically insignificant for these types of structures when compared to autogenous shrinkage.

(5) Reinforcing. Since excluding reinforcing from an analysis provides conservative results, initial analyses can be performed without the effects of reinforcement. The effects of reinforcing on resulting structural behavior are small if no cracking occurs, but if cracking does develop, modeling of the reinforcement can be very beneficial for control of the cracking.

(6) Crack model. The cracking model used in a NISA is a smeared crack approach. This approach will predict the general extent of cracking occurring but does not directly predict the exact length of cracks or the crack mouth opening displacements. A discussion of the smeared crack model and how it is implemented in the analysis is given in paragraph A-5*e*(4) and in Annex 2 of Appendix A.

f. Parameters affecting cracking in mass concrete.

(1) Restraint of volume change. Cracking in mass concrete is primarily caused by restraint of volume change. These volume changes may be due to heat generation and subsequent cooling, autogenous shrinkage, creep/stress relaxation, or other mechanisms. Restraint limits the changes in dimensions and causes corresponding tensile, compressive, torsional, or flexural stresses in concrete. Of primary concern in mass concrete structures is restraint which causes tensile stresses and corresponding tensile strains. Restraint may be either external or internal. External restraint is caused by bond or frictional forces between the concrete and the foundation or underlying and adjacent lifts. The degree of external restraint depends upon the relative stiffness and strength of the newly placed concrete and the restraining material and upon the geometry of the section. Abrupt dimensional changes or openings in a monolith such as wall offsets, culvert valve shafts, gallery entrances and offsets, reentrant corners, etc., have caused external restraints that have resulted in cracking in existing structures. Internal restraint is caused by temperature gradients within the concrete. The warmer concrete in the interior of the mass provides restraint as the concrete in the periphery of the mass cools at a different rate due to heat transfer to its surroundings. The degree of internal restraint depends upon the total quantity of heat generated, the severity of the thermal gradient, the thermal and mechanical properties of the concrete, and thermal boundary conditions.

(2) Material parameters. A number of material parameters can affect cracking related to restrained volume change. They include: (a) heat generation of the concrete; (b) mechanical properties of the concrete including compressive and tensile strength, tensile strain capacity, modulus of elasticity, linear coefficient of thermal expansion, and creep/stress relaxation; (c) autogenous shrinkage of the concrete; and (d) thermal properties of the concrete including specific heat and thermal conductivity. These concrete properties are governed by the selection of materials used to make the concrete, including cementitious materials (portland cement type, ground granulated iron blast furnace slag, and pozzolans such as fly ash), aggregates, chemical admixtures, etc., and by the proportions of these materials in the concrete mixture. Many of these properties are also dependent upon the maturity of the concrete and are thus time and temperature dependent. Optimization of the selection of concrete mixture materials and proportions should be a part of a properly conducted concrete materials study. Due consideration should be given to the performance and economy of the

mixture. The study should be conducted according to the guidance in EM 1110-2-2000, Standard Practice for Concrete, and should be documented in a concrete materials design memorandum.

(3) Construction parameters. A number of construction parameters can affect cracking due to restrained volume change. They include: (a) lift height, (b) time between placement of lifts, (c) concrete placement temperature, (d) use of insulation, and (e) monolith geometry including section thickness, monolith length, and location and size of inclusions such as galleries, culverts, etc. In addition, the time of year that a monolith is constructed can be controlled if it has been determined by a NISA that a particular start date for construction is beneficial. Any construction requirements or restrictions identified by a NISA must be clearly stated in the construction contract documents. When optimizing these construction parameters, due consideration should be given to common construction practices, economy, and constructability.

A-2. Analysis Requirements

a. General. Nonlinear incremental structural analyses on MCS should be performed using material property combinations of creep, shrinkage, and aging modulus coupled with two dates for start of construction. The specified combinations of these parameters are only a minimum, therefore, engineering judgement should be used to ensure that all possible critical combinations are included in the analyses for the evaluation and design of the structure. Deletion of any of the specified combinations requires consultation with and approval by the Structures Branch, Headquarters (CECW-ED).

b. Material property combinations. The minimum combinations of material properties for the purpose of analyzing and evaluating a MCS are shown in Table A-1.

(1) Common analysis parameters. The analysis can be performed within ABAQUS by using a time-history analysis where the elements and loads are activated as prescribed by the proposed construction schedule and the ambient temperature is modified as construction proceeds through different seasons of the year. The NISA should be performed using a set of common parameters for the concrete, loading, and ambient conditions. The common parameters are the concrete's aging modulus and maximum adiabatic temperature rise data, the extreme ambient temperature data, the incremental gravity loads, and the constant service loads. The aging modulus is represented by data reflecting the time variation of Young's Modulus as a function of the age of the concrete and is further discussed in paragraph A-3*b*(2)(a). The maximum adiabatic temperature rise reflects the temperature rise within the concrete due to hydration of the cementious materials and is further discussed in paragraph A-3*b*(1)(a). The extreme ambient condition is defined in paragraph A-2*c*, the gravity loads are described in paragraph A-5*e*(1), and the service loads are described in paragraph A-2*f*.

(2) Maximum and minimum material properties. The terms maximum and minimum refer to a set of bandwidths reflecting the uncertainty involved in the use of these parameters as discussed in paragraph A-1*e*(1)(a). Minimum refers to using the material test data multiplied by one minus the specified decimal percentage, and maximum refers to using the material test data multiplied by one plus the decimal percentage. The material test data bandwidth percentages for creep, shrinkage, and adiabatic temperature rise will be +/- 15 percent. These are the minimum accepted bandwidths and can be reduced only after consultation with and approval by the Structures Branch and Geotechnical Branch, Headquarters, (CECW-ED and CECW-EG).

Table A-1
Material Property Combinations

	Young's Modulus	Creep	Shrinkage	Adiabatic Temperature Rise	Mechanical Loads
1	Aging	None	None	Maximum	Gravity + Service
2	Aging	Minimum	Minimum	Maximum	Gravity + Service
3	Aging	Minimum	Maximum	Maximum	Gravity + Service

(3) Material property combination 1. This material property combination is to be used as a baseline for comparison with combinations 2 and 3. *This material property combination is not to be used for design purposes.* Comparing combination 1 with 2 and 3 provides insight into the effects of the time-dependent creep and shrinkage. Material property combination 1 also provides insight with respect to a traditional heat transfer analysis by including only the adiabatic temperature rise and the extreme ambient conditions. This material property combination should include the incremental construction.

(4) Material property combinations 2 and 3. Combinations 2 and 3 are essential in meeting the objectives of a NISA. These material parameter combinations have been critical combinations in previous studies. (Truman, Petruska, and Ferhi 1992; Garner et al. 1992)

c. Extreme ambient temperature. The extreme ambient temperature data should be obtained from a weather collection site near the project site. The data required is the coldest recorded monthly average temperature for each month within any given year and the hottest recorded monthly average temperature for each month within any given year. An extreme ambient temperature function should be developed as a sine wave with a 365-day period which captures the coldest and hottest of the extreme monthly average temperatures. The extreme ambient temperature is used to account for the possibility of seasons (months) having much higher or lower temperatures than the average ambient conditions developed using monthly averages based on multiyear averages. The weather collection sites and the associated data may be obtained from the Air Force liaison of the National Climatic Data Center, Federal Building, 37 Battery Park Ave., Asheville, NC, 28801-2733, (704) 271-4218.

d. Construction start-date parameters. Combinations 1, 2, and 3 will be used in conjunction with a single start date. Then the controlling combination of either material parameter combination 2 or 3 must be used with a second start date. The second start date should be selected to provide an opposing ambient condition to the original start date. (The first start date could be in June; the second could be in January.) The selection of start dates is structure and site dependent and should be evaluated by the design team. A single start date is inadequate for producing the worst conditions at every location within the structure, since the structure is built in lifts (increments) over a significant period of time. A start time in the winter could be critical for lift one but could also result in a later lift being placed in the spring. This timing could cause a less critical situation for the second lift than if it were also placed in the winter. Therefore, the design team should locate critical regions (high stress, high strains, potential cracking) within the structure and use start dates which cause early exposure of these critical areas to the coldest and warmest times of the year. The design team should be aware that the steeper the temperature gradient within the material, the higher the stress. Therefore, the start date should be chosen to create the highest or steepest internal gradient in those areas cited as critical. The highest gradient in an area would typically occur when the two extremes of the internal heat generation and ambient conditions are 180 deg out-of-phase. Since this situation cannot be explored for every critical area, the design team must develop a sound strategy for choosing the two start dates.

e. Time duration. The time duration used in a NISA should be sufficient to guarantee the inclusion of the maximum or critical response of the structure. However, neither the maximum nor critical response occurrence time is generally known prior to an analysis. For this reason, the time duration used in a NISA should last a minimum of one full ambient temperature cycle past the time of service load application. The minimum time duration may be reduced if parametric studies indicate the time at which the maximum or critical structural response occurs is less than the specified minimum.

f. Service loads. Service loads shall be applied during the time increment beginning 100 days after placement of the last lift in the analytical model. Generally, changes in film coefficients and ambient conditions due to the application of service loads need not be considered in the heat transfer analysis. For example, the thermal effect of water need not be considered in the heat transfer analysis, but the weight and pressure due to water must be included in the stress analysis. This simplification, although theoretically inconsistent, reduces the complexity of the analysis process. The simplification may be inappropriate when the minimum ambient air temperature is much less than the water temperature. If portions of the structure show high crack potential, then time-history plots at these locations should be examined to see the effect of service load application.

In cases where the application of service load has reduced the crack potential, there must be a reanalysis without service loads to determine the crack potential for those monoliths constructed at early times when service load application is more than 1 year away.

g. Parametric studies. Material property combinations may be supplemented through the use of additional parametric studies. A parametric study is a rationally planned set of analyses used to gain a better understanding of structural response through the identification and understanding of the effects that critical parameters have on the structure. The effects of a parameter on the structure can be determined by varying that parameter in a set of analyses while holding the other parameters constant. Likely candidates for a parametric study are, but are not limited to, determination of the critical material property combination, analysis duration, type of analysis (i.e., plane stress or plane strain), critical lift sequence or configuration, analysis start time, critical material properties, insulation requirements, and placement temperatures. Results from single analyses within the parametric study should be interpreted separately to gain an understanding of the structural response in each analysis. Then comparisons of results from each analysis in the parametric study can be made and the influence of each parameter identified. Once identified and documented, results and conclusions from parametric studies can be used in subsequent NISA phases. For example, assume a goal of a current NISA study is to reduce construction costs through relaxing controls on concrete placement temperatures. A parametric study is devised permitting only the lift placement temperature to vary. Results are analyzed, and the highest acceptable placement temperature is selected for subsequent use.

A-3. Material Properties

a. General. Information on the thermal, mechanical, and physical properties are required for the concrete mixtures, foundation materials, and air. If the foundation includes piles, they will be modeled in the analysis and their stiffness properties will be input into ABAQUS. Some of these properties are time dependent, while others are assumed to remain constant with respect to time. Test methods identified as ASTM are American Society for Testing and Materials, Philadelphia, PA, methods. Test methods identified as CRD-C (Concrete Research Division-Concrete) are Corps of Engineers methods found in the Handbook for Concrete and Cement published by the U.S. Army Engineer Waterways Experiment Station (WES) (1949a). Test methods identified as RTH (Rock Testing Handbook) are Corps of Engineer methods found in the Rock Testing Handbook (USAEWES 1990). The units listed in the following discussion are those normally associated with the respective material property/test method. The units input into to the ABAQUS program may vary; see paragraph A-5*a*(4), Units, for further discussion.

b. Concrete properties. The following thermal, mechanical, and physical properties must be determined as input to a NISA. Some of the properties will be determined by laboratory testing and some will be assigned jointly by the materials and structural engineers. Properties that are determined in laboratory tests should be representative of concrete mixtures containing project specific materials. The test data and curves defining the time relationships should be documented in the concrete materials design memorandum. The following properties will be determined in the laboratory prior to start of a NISA.

(1) Thermal properties.

(a) Adiabatic temperature rise. An adiabatic system is a system in which heat is neither allowed to enter or leave. The adiabatic temperature rise, therefore, is the change in temperature due to hydration of the cementitious materials in a concrete mass when adiabatic conditions exist. It is a measure of the heat evolution of the concrete mixture and serves as the loading in the heat-transfer analyses. In very large masses of concrete, temperatures near the center of the mass will peak near the sum of the placement temperature and the adiabatic temperature rise. Nearer the surface of the placement, the peak temperature will be lower and will be near ambient air temperature. Adiabatic temperature rise is determined according to CRD-C 38 (USAEWES 1949a). The rate of heat evolution depends on the amount and type of cementitious materials in the mixture and on the temperature of the test specimen at the beginning of the test. Because of this dependence on the temperature of the test specimen, the total amount of heat generated at any given time will also be different. The peak temperature and the shape of the curve can vary significantly for different concrete mixtures. Therefore, concrete used in the test should closely represent concrete that will be used for the project and the placement temperature for the test should be

at or near the anticipated project maximum placement temperature. If experience does not allow for reasonably accurate estimation of the maximum placing temperature, tests should be conducted at a lower and upper temperature to bracket the temperature rise. Typical values for adiabatic temperature rise for mass concrete range from 20 to 35 °F at 5 days to 30 to 45 °F at 28 days. A curve of temperature rise versus time will be input into the ABAQUS program through the user subroutine DFLUX or HETVAL as discussed in paragraph A-5*a*(2).

(b) Specific heat. Specific heat is the amount of heat required per unit mass to cause a unit rise of temperature. Specific heat is also referred to as heat capacity. It is affected by temperature changes, but for the range of temperatures expected in a NISA, it should be assumed to be constant. The specific heat is determined according to CRD-C 124 (USAEWES 1949b). The test should be conducted at an age of at least 7 but not more than 28 days. Typical values for specific heat of mass concrete range from 0.18 to 0.28 Btu/lb-°F.

(c) Thermal diffusivity. Thermal diffusivity is a measure of the rate at which temperature change can occur in a material. It is determined according to CRD-C 36 (USAEWES 1949c) for conventional concrete and CRD-C 37 (USAEWES 1949d) for mass concrete. The test should be conducted at an age of at least 7 but not more than 28 days. Typical values for thermal diffusivity of mass concrete range from 0.03 to 0.06 ft^2/hr. The value of thermal diffusivity is not input into ABAQUS but is used to calculate the thermal conductivity of the concrete.

(d) Thermal conductivity. Thermal conductivity is defined as the quantity of heat flowing through a unit thickness over a unit area of the material subjected to a unit temperature difference between the two faces. This parameter is most sensitive to the proportion of cement paste, free water, and aggregate. It is calculated from the thermal diffusivity and specific heat according to CRD-C 44 (USAEWES 1949f). Thermal conductivity of mass concrete is not significantly affected by changes in temperature over typical ambient temperature ranges. Typical values for thermal conductivity of mass concrete range from 1 to 2 Btu/ft-hr-°F.

(2) Mechanical properties.

(a) Modulus of elasticity. The modulus of elasticity is defined as the ratio of normal stress to corresponding strain below the proportional limit. For practical purposes, only the deformation which occurs during loading is considered to contribute to the strain in calculating the modulus of elasticity. Subsequent increases in strain due to sustained loading are referred to as creep. The modulus of elasticity is a function of the degree of hydration and therefore is time dependent. It is also temperature dependent; however, the effect within the range of temperatures involved in a NISA is negligible and therefore is not modeled in ABAQUS. The modulus of elasticity is determined according to CRD-C 19 (USAEWES 1949e). To adequately model the time dependency of the modulus of elasticity, tests should be conducted at ages of 1, 3, 7, 14, 28, 56, and 90 days, as well as the design age. Typical values for the modulus for mass concrete are about 1×10^6 psi at 1 day and about 5×10^6 psi at 90 days. A curve of modulus versus time will be input into ABAQUS through the UMAT subroutine.

(b) Poisson's Ratio. Poisson's Ratio is defined as the ratio of the lateral to the longitudinal strain resulting from a uniformly distributed axial stress. It is determined according to CRD-C 19. Typical values for Poisson's Ratio for mass concrete range from 0.15 to 0.20. The value input into ABAQUS should be based on test data at ages greater than 7 days and on engineering judgement.

(c) Creep. Creep is defined as time-dependent deformation due to sustained load. Creep results in a progressive increase in strain under a state of constant stress. Creep is closely related to the modulus of elasticity and compressive strength of the concrete and is thus a function of the age of the concrete at loading. Creep is determined according to CRD-C 54 (USAEWES 1949g). For purposes of a NISA, at least three ages of loading should be conducted: 1 day, 3 days, and 14 days. Typical values for creep of mass concrete are about 1×10^{-6} microns/psi at a test age of 60 days for a specimen loaded at 1 day age and about 0.2×10^{-6} microns/psi at a test age of 60 days for a specimen loaded at 14 days age. A curve of creep which is a function of the modulus

and time is contained in ABAQUS through the UMAT subroutine and must be calibrated for each project's selected mixture.

(d) Autogenous shrinkage. Autogenous shrinkage is a decrease in volume of a concrete specimen or member due to hydration of the cementitious materials without the concrete gaining or loosing moisture. This shrinkage is also referred to as "sealed length change." This type of volume change occurs in the interior of a large mass of concrete. For small volumes of concrete, such as structural concrete members, the magnitude of autogenous shrinkage is negligible compared to drying shrinkage and thus is usually not distinguished from drying shrinkage. However, for large mass concrete structures, autogenous shrinkage can be a significant factor. Autogenous shrinkage occurs over a much longer time than drying shrinkage, the localized phenomenon that affects only a thin layer of concrete near the surface. Autogenous shrinkage tends to increase at higher temperatures, with higher cement contents, and with finer cements. This property is modeled as a function of time in the analyses. Typical values for mass concrete vary significantly depending on the test procedure utilized. Melvin Price Locks and Dam values were about 300, 350, and 400 millionths at 10, 25, and 50 days, respectively. Olmsted Lock values were about 20, 30, and 45 millionths at 10, 25, and 50 days, respectively. A curve of shrinkage versus time will be input into ABAQUS through the UMAT subroutine. No standard test method exists for determining the autogenous shrinkage of a concrete mixture. However, recent experience at WES for the Olmsted Locks Project has shown that properly prepared and instrumented sealed creep cylinder specimens with no load applied can be used to measure autogenous shrinkage. Method CRD-C 54, (USAEWES 1949g) describes the preparation of creep test specimens. Autogenous shrinkage specimens must by completely wrapped in a moisture retentive membrane to minimize loss of water to the surroundings. This can be verified by periodic determinations of the mass of the autogenous shrinkage specimens to determine if the specimen mass is remaining constant or varying with time. WES Technical Report SL-91-9 (Hammons et al. 1991) documents the test procedure and results obtained for the Olmsted Locks project.

(e) Coefficient of thermal expansion. The coefficient of thermal expansion is the change in linear dimension per unit length per unit of temperature change. The coefficient of thermal expansion is determined according to CRD-C 39 (USAEWES 1949h). The value of this property is strongly influenced by the type and quantity of coarse aggregate in the mixture. The coefficient of thermal expansion for mineral aggregates varies from less than 2 to over 8×10^{-6} in./in./°F, while the coefficient of thermal expansion for cement paste may vary from 6 to 12×10^{-6} in./in./°F. Typical values for the coefficient of thermal expansion for mass concrete range from 4 to 6×10^{-6} in./in./°F.

(f) Tensile capacity. The cracking resistance of concrete is determined by a combination of limiting tensile strain and tensile stress. These properties are time and rate of loading dependent. They are determined according to CRD-C 71 (USAEWES 1949i). Results from the slow load tests as defined in the test method are required to define the failure envelope for the concrete cracking criteria. Refer to paragraph A-6*d*, Cracking criteria, and Annex 2 of Appendix A for use of the test results. Typical values for tensile strain capacity of mass concrete for a slow load test for a specimen loaded at 7 days and failing at between 75 and 150 days range from 75 to 150 microns.

(3) Physical property. Density is defined as mass per unit volume. It is determined according to CRD-C 23 (USAEWES 1949j). Typical values of density for mass concrete range from 140 to 160 lb/ft^3.

c. Foundation properties. The thermal and physical properties of the foundation are dependent on the type of soil or rock, the moisture content, the presence of piles, and any discontinuities in the foundation. In situ properties may vary significantly from those obtained from laboratory testing of small samples obtained from borings or test pits. Exact thermal properties are not necessary for the foundation materials and adequate values for use in a NISA may be obtained from Jumikis (1977) or Kersten (1949). Likewise, exact mechanical properties are not required, and adequate values can be estimated from foundation test data or from Hunt (1986). The structural and geotechnical engineers should jointly select foundation properties for ABAQUS input based on any in situ properties available and varied based on information from the above referenced texts and past experience.

(1) Thermal properties.

(a) Thermal conductivity. The thermal conductivity of the foundation material is affected by density and moisture content. The thermal conductivity of foundation materials ranges from 2.4 for clay to 2.8 for sand to 3.0 for gravel and from 2.4 for limestone to 3.1 Btu/ft-hr-°F for granite. Thermal conductivity can be determined according to CRD-C 44 (USAEWES 1949f).

(b) Specific heat. Specific heat for foundation materials ranges from 0.22 for clay to 0.19 for sand and from 0.22 for limestone to 0.19 Btu/lb °F for granite. Specific heat can be determined according to CRD-C 124 (USAEWES 1949b).

(2) Mechanical properties.

(a) Modulus of elasticity (Young's Modulus). The modulus of elasticity of foundation materials varies greatly with the grain size, moisture content, and degree of consolidation. Adequate values for soils can be estimated by the geotechnical engineer. Values for foundation rock can be determined by ASTM D 3148 (ASTM 1992a); typical values range between 4 and 7×10^6 psi for granite and between 2 and 6×10^6 psi for limestone.

(b) Poisson's Ratio. As with the modulus of elasticity, adequate values for Poisson's Ratio for foundation soils can be estimated by the geotechnical engineer. Values for foundation rock can be determined by ASTM D 3148; typical values range between 0.25 and 0.33 for both granite and limestone.

(c) Coefficient of thermal expansion. Soil foundations will be modeled in the heat transfer analysis only and, therefore, the coefficient of thermal expansion is not needed. The coefficient of expansion for rock types can be determined according to ASTM D 4535 (ASTM 1992b); typical values are 4.4×10^{-6} in./in./°F for both limestone and granite.

(d) Pile-subgrade reaction modulus. The pile-subgrade reaction modulus should be determined in accordance with the guidance given in EM 1110-2-2906, Design of Pile Foundations, 15 January 1991.

(3) Physical properties.

(a) Density and moisture content. The density and moisture content of the foundation material must be determined by the geotechnical engineer. The in situ density of a soil foundation can be estimated from boring data by means of ASTM D 1586 (ASTM 1992c). Undisturbed samples of soil can be tested in accordance with EM 1110-2-1906, Laboratory Soils Testing; and undisturbed samples of rock can be tested in accordance with the Rock Testing Handbook (USACE 1990).

(b) Initial temperature. The initial temperatures for the foundation should be provided as a distribution of temperature with depth. These distributions should be determined from a heat transfer analysis of the foundation for a period of not less than 1 year proceeding the start of concrete placement.

d. Air properties.

(1) General. Several parameters are required to model the air trapped within culverts, galleries, or other enclosed voids for the heat transfer analysis. These properties should be assigned by the structural engineer and they are assumed to be constant during the analysis. The key parameters are listed below and have similar definitions to those presented in paragraph A-3*b*. Film coefficients can be used in lieu of air elements in the analysis. A film coefficient of 0.01 Btu/day-in.^{2}-°F should be used.

(2) Thermal properties. The required thermal properties are the thermal conductivity and specific heat. Reasonable values are 0.00126 Btu-in./hr-in.^{2}-°F for thermal conductivity and 0.24 Btu/lb-°F for specific heat.

(3) Physical property. The density of air must be input into the analysis. A density of 0.000046 lb/in.^{3} should be used for the analyses.

A-4. Construction Parameters

Differences in the way a monolith is constructed will impact the behavior of a structure to varying degrees. The response of the structure to changes of the construction parameters in the analysis will often dictate whether or not cost reducing measures can be taken in the field. Construction parameters can also be varied in an attempt to improve the performance of a structure. The paragraphs below describe the primary construction parameters that can be considered for changes during the NISA for accomplishing cost reductions or improved structural behavior. Values

for the following parameters must be selected by the design team prior to the initial analysis.

a. Lift heights. Since the heat escape from a mass is inversely proportional to the square of its least dimension (ACI 207 (1992a)) and since the height of a lift will usually be the smallest dimension, the height of a lift can become a factor in the behavior of a mass concrete structure. Lift heights to be used in initial analyses will typically be selected by the design team based on previous experience and practical limits. If the initial analyses indicate that the behavior of the structure is satisfactory, then analyses may be performed with increased lift heights as a measure for reducing costs as was done for the auxiliary lock at Melvin Price Locks and Dam (Truman, Petruska, Ferhi 1992). Likewise, if results indicate unacceptable behavior, a decrease in lift heights may be considered to alleviate problems in the structure. Changing lift heights can be accomplished in the numerical model as described in paragraph A-5*c*(3).

b. Placement intervals. The time allowed between the placement of lifts can have an effect on the performance of the structure due to the insulating effect a new lift has on the previous lift(s). In addition, the structural performance can be affected by the difference in modulus of the two lifts and the fact that creep and shrinkage in the older lift are occurring at a lower rate than for a newly placed lift. A 5-day interval between lift placements is typically assumed. The longer the interval between placement of lifts, the longer each lift will have to dissipate the heat that has built up within the lift. When considering the aging characteristic of concrete, however, longer placement intervals may not be desirable, since the previous lift will be much stiffer than the new lift providing more restraint to the new lift. Lift placement interval can have an effect on the construction cost if the change increases the length of the contract. If stresses at the early times are high using the typical 5-day interval, then the design team may choose to consider analyses which use longer placement intervals. In the analysis, this requires changing the time-history designations to the appropriate values and ensuring that the values for the reference time in the material input are properly set.

c. Placing temperatures. For many mass concrete structures, the temperature of the concrete at the time of placement is limited to reduce the temperature level within the mass due to the heat of hydration. The placing temperature for the initial analysis should be established by the materials engineer as described in paragraph A-3*b*(1)(a). As with lift heights, if structural behavior is acceptable then consideration may be given to increasing the placing temperature. Increasing the placing temperature can lead to cost savings due to decreased cooling requirements. Changing the placing temperature is a simple change to the initial conditions in the heat transfer analysis.

d. Start time. The time of year at which an analysis is started can have a significant effect on the analytical results. Analyses in the past have been started in a time frame which has the largest mass placed at the hottest time of the year. It was felt that this would create the highest temperatures within the structure and likewise create the highest stresses. Winter starts can also be critical due to the temperature gradients that will occur within the structure at these times. As stated in paragraph A-2*d*, a minimum of two NISA's should be performed using different start times. Each project should be evaluated by the design team to determine if there are additional start times which could result in a critical condition based on past experience and engineering judgment. Changing the start time in the analysis will require the ambient temperature curve to be adjusted so that it corresponds to the given time of year that the analysis is being started.

e. Insulation. Insulation of the concrete during cold weather may be necessary during construction and if used must be accounted for in the analysis. The time that insulation is in place and the amount of insulation (the R value) to be used will depend on the project location and should be selected by the design team for the initial analysis. Both of these parameters may be varied during subsequent analyses to achieve cost savings or to improve performance. Any changes made in the insulation requirements should be coordinated among the design team members. Changes in insulation are accounted for in the analysis by changing the film coefficients which model the convection across the boundary. Instructions for calculating these coefficients are given in paragraph A-5*d*(3).

f. Vertical construction joints. There may be some projects where vertical construction joints become necessary due to excessively large concrete placements. If this is the case, lift sequences creating vertical joints should be accounted for in the

incremental construction analysis procedure. Stresses across a vertical construction joint should be examined closely for determination of any special measures that should be taken during the design and construction of the joint (e.g., placement of reinforcement bars across the joint face). In addition, performance of a 3-D or a 2-D analysis in the longitudinal plane should be considered for monoliths with vertical construction joints to confirm results obtained in the 2-D analysis of the transverse plane. The reason for this is that the joint itself may be located in the out-of-plane direction. Changes in vertical construction joints may require changes to an existing mesh but, as a minimum, will require changes in the input with respect to the element set definitions.

g. Embedded cooling coils. Cooling coils to reduce heat within an MCS have been used in some large gravity and arch dam projects but have typically not been needed on navigation type structures. If placing temperatures have been reduced to their lower limit, lift heights have been reduced to a practical minimum, and temperatures within the structure remain excessive, then the addition of cooling coils should be considered. This can be accomplished in ABAQUS by using the CFLUX command and specifying temperatures at nodes at or near locations of cooling coils.

h. Geometry. The geometry of the structure is of course a major contributing factor to the behavior of the structure. Therefore, a NISA should not be performed until the structural geometry is at a stage where only minor changes to the geometry are expected. While this parameter may be more difficult than other parameters to alter, there may be instances where it will be necessary to make this type of change. If a change is made to the geometry of the structure, then coordination between all disciplines is a necessity to ensure the change does not have an adverse effect on some other function of the structure. A change in the geometry will generally require some type of revision to the mesh of the model.

i. Reinforcing. Reinforcing is an integral part of many of the MCS's used within the Corps of Engineers, but to date there has been limited use of reinforcing in NISA's. This was because many of the structures analyzed to date had no cracking problems and adding reinforcing in a model when cracking is not occurring has little effect on results. If an analysis predicts cracking in a structure, then reinforcement should be included in the model to determine the benefits of the reinforcing prior to evaluating any other measures to eliminate the cracking. Modeling of reinforcement should be done using the ABAQUS *REBAR option and not with discrete truss elements. For information on the modeling of reinforcement, refer to the WES report, "Use of Reinforcement in a Nonlinear, Incremental Structural Analysis" (Fehl and Merrill in preparation).

A-5. Structural Modeling and Analysis

a. Finite element code.

(1) Software requirements. The FE code ABAQUS (Hibbitt, Karlsson, and Sorensen 1989) in conjunction with the concrete constitutive model contained in ANACAP-U (ANATECH Research Corp. 1992) should be used for performing a NISA as described within this document. The modeling techniques for performing a NISA have all been established using ABAQUS and the ANACAP-U software. Should extenuating circumstances arise which preclude the use of ABAQUS or ANACAP-U, a full evaluation of the code selected must be made including comparisons to results obtained using ABAQUS and ANACAP-U on full-scale problems. In addition, use of an FE code other than ABAQUS and a constitutive model other than ANACAP-U must have the approval of CECW-ED.

(2) Heat generation subroutines. The subroutines DFLUX and HETVAL are used by ABAQUS to define the heat generation for input into the heat transfer analysis and either of these subroutines may be used. The adiabatic temperature rise curve obtained from testing is used in the subroutine, and the volumetric heat generation rate is calculated from this curve to provide time-dependent heat generation to ABAQUS in performing the heat transfer analysis. Annotated examples of the DFLUX and HETVAL subroutines are given in Annex 3, Appendix A. Both will accomplish the task of providing the internal heat generation due to the heat of hydration. The difference in the two subroutines is that DFLUX is activated through control of the element numbers while HETVAL is activated through the use of an assigned material name for each concrete lift. Both DFLUX and HETVAL are user supplied subroutines which must be developed for each project.

(3) Material model subroutine. UMAT is a user subroutine in the stress analysis portion of NISA that

contains the material model for the time-dependent properties for creep, shrinkage, and the aging modulus of elasticity. Other parameters used within the UMAT subroutine are Poisson's Ratio, the cracking strain, the coefficient of thermal expansion, bandwidth factors for creep and shrinkage, the time of set, and the 3-day compressive strength of the concrete (Annex 4, Appendix A, is a complete list of input parameters required for a NISA). Curves contained in the material model must be fitted for the concrete mixture which is expected to be used at the project site. This curve fitting is currently performed by CEWES-SC, but efforts are in progress to implement a procedure which will allow curve fitting to be accomplished by others. The material model used in UMAT was developed by ANATECH Research Corp. and is contained in the ANACAP-U software (ANATECH Research Corp. 1992). The mathematical relationships adopted for the material properties contained in the subroutine are contained in the ANACAP-U Theory Manual (ANATECH Research Corp. 1992). In addition, ANACAP-U uses a smeared crack model (discussed in further detail in paragraph A-5*e*(4), Appendix A) where cracking occurs at the integration points. The cracking criteria is based on an interaction curve between stress and strain (ANACAP-U Research Corp 1992). There is a brief description of the cracking model in Annex 2, Appendix A.

(4) Units. The ABAQUS code does not provide an input option for different units for different parameters, therefore the user must ensure that all of the input parameters have consistent units. The preferred units are:

Length - inches

Weight - pounds

Stress - lb/in.^{2}

Time - days

Temperature - °F

Heat - Btu

b. 2-D versus 3-D analysis. There are many MCS for which a 2-D analysis of a monolith will be sufficient. However, any structure undergoing temperature loadings exhibits some 3-D behavior, even traditionally 2-D type structures. While it may be desirable to perform 3-D analyses on all structures, the complexity associated with performing 3-D analyses is such that this approach is not yet practical. Therefore, 2-D analyses of transverse strips should be used for most investigations. Additionally, behavior of the structure in the out-of-plane direction may be determined using 2-D strips in the longitudinal direction and/or a 3-D analysis. The primary purpose of a 3-D analysis should be for cases where 2-D analysis is inappropriate because of geometrical configuration or loading conditions.

c. Mesh generation and refinement. Conventional FE modeling techniques should be applied to develop an FE mesh for a NISA (ETL 1110-2-332, "Modeling of Structures for Linear Elastic Finite Element Analysis," and Technical Report ITL-87-8, "Procedure for Static Analysis of Gravity Dams Using the Finite Element Method - Phase Ia" (Will 1987)). In addition, consideration should be given to the items discussed below.

(1) General. Typically, the mesh developed for use in the heat transfer analysis will be used in performing the stress analysis. Using the same mesh for both analyses ensures that each node in the stress mesh has a temperature associated with it from the heat transfer mesh. In addition to items discussed in subsequent paragraphs, the designer should attempt to include at least two elements through the thickness of any member.

(2) Foundation. For soil-founded structures, the soil elements used in the heat transfer analysis are usually replaced by springs in the stress analysis to save computing time. A similar approach may be used for rock foundations but may require some investigative analysis since, to date, no NISA's have been performed on rock-founded structures. Another possibility for rock foundations is the use of superelements which allows for the stiffness of a large number of discrete elements to be lumped into a single region which is the superelement. Despite the method used, a rock foundation should model an area 1.5 times as deep and 3.0 times as wide as a structure's base as established in "Static Analysis of Gravity Dams Using the Finite Element Method, Foundation Effects - Phase Ib" (Jones and Foster in preparation).

(3) Inclusion of lift joints. Development of an FE mesh for a NISA study must account for the locations of the construction lift joints and vertical

construction joints. Construction lift joints must be treated the same way as any other face of a structure. A construction lift joint or vertical construction joint cannot be contained within an element; it must be at the interface of a row of elements. Therefore, if analyses with different lift joint locations are anticipated, the FE mesh should be developed so that the revised locations can be accommodated. Accommodating such changes should also account for inclusion of at least two elements in each lift. If the FE mesh can accommodate the new locations, then the only change needed for the ABAQUS input is to redefine the sets of elements associated with each lift.

(4) Preprocessing. There are various programs available that may be used to provide preprocessing capabilities in developing a mesh. If a decision is made to use a preprocessor, users should select a preprocessor with which they are familiar or feel they can learn easily. The user must determine the preprocessor's compatibility with ABAQUS. One possible choice for a preprocessor would be the preprocessing portion of the ANACAP-U software (ANAGEN, described in the ANACAP-U User's Manual (ANATECH Research Corp 1992)) which allows the user to define various key nodes in the geometry of the structure and then requires specification of the mesh density, thereby generating the mesh. In a similar manner, node sets and element sets may be defined.

(5) Element size limitation. Due to the formulation of the heat transfer algorithm used in ABAQUS, there is a criterion which relates the length of the timestep to the size of the elements being used. Violation of the criterion could lead to numerical inaccuracies in the solution which could introduce errors into the temperature values computed. Due to concerns about capturing the heat generated at early times and the length of the timesteps needed to capture this behavior, the length of the timestep is the controlling factor and must be used to compute the element size. The size of the element is therefore limited by the following equation:

$$\Delta L^2 < \frac{6k\Delta t}{\rho c} \qquad \text{(A-1)}$$

Δt = *time increment* (*days*)

ρ = *density* ($lb/in.^3$)

c = *specific heat* ($Btu/lb\text{-}^\circ F$)

ΔL = *length between adjacent nodes of an element* (*in.*)

While every effort should be made to adhere to the equation given above, it may become necessary, particularly in 3-D analyses, to exceed this criteria to enable a problem to be solved. Truman, Petruska, and Ferhi (1992) have shown that exceeding the above criteria in the direction perpendicular to heat flow is acceptable. This information can be utilized in long slabs or thin walls where the direction of heat flow is generally in one direction.

d. Heat transfer analysis.

(1) Ambient temperature. Once the data for the ambient temperature have been developed as described in paragraph A-2*c*, this appendix, it can be put into the ABAQUS input file using the *AMPLITUDE card. This will provide an average daily temperature curve. The data can be input in 5-to 10-day increments, and the analysis will linearly interpolate between the values provided for times in the analysis when a value is not specifically given.

(2) Cold fronts. The passage of cold fronts where the temperature drops significantly over a short period of time can be a critical factor when evaluating the cracking taking place during mass concrete construction. Explicit modeling of cold fronts is not required in a NISA, but the effects cold fronts can have on the behavior of the structure should be considered as described in paragraph A-6*d*(3), this appendix. The fact that initial conditions are conservatively selected by the design team and that extreme ambient conditions are used as well as the reduced evaluation criteria discussed in paragraph A-6*d*(3) provide the justification for not requiring a specific cold-front analysis. If the criteria in paragraph A-6*d*(3) is exceeded, then changes to the insulation may be required. The film coefficient value for insulation can be used for a longer period of time in the analysis, and an increased amount of insulation can be modeled by decreasing the value of the film coefficient as described in the following paragraph A-5*d*(3).

(3) Film coefficients. An essential part of the heat transfer analysis is to model convection which is

the heat transfer that occurs between a fluid (e.g., air or water) and a concrete surface. The following equations are from the ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) Handbook and Product Directory-1977 Fundamentals (1977). These equations may be used for computing the film coefficients to be included in ABAQUS for modeling convection. For surfaces without forms, the coefficients should be computed based on the following:

$$h = 0.1132V^{0.8} \quad \text{for } V > 10.9 \text{ mph} \tag{A-2}$$

and

$$h = 0.165 + 0.0513(V) \quad \text{for } V < 10.9 \text{ mph} \tag{A-3}$$

where,

$$h = \textit{film coefficient}\left(\frac{Btu}{day\text{-}in.^2\text{-}^\circ F}\right)$$

$$V = \textit{wind velocity}(mph)$$

The wind velocity may be selected based on monthly average wind velocities at the project site. Data can be obtained from the National Climatic Data Center for a given location and can be generalized over a period of several months for input into the analysis. If forms and insulation are in place, then the values for h computed in the equations above should be modified as follows:

$$h' = \frac{1}{\left(\frac{b}{k}\right)_{formwork} + \left(\frac{b}{k}\right)_{insulation} + \left(\frac{1}{h}\right)} = \frac{1}{R_{formwork} + R_{insulation} + \left(\frac{1}{h}\right)} \tag{A-4}$$

where

$$h' = \textit{revised film coefficient}\left(\frac{Btu}{day\text{-}in.^2\text{-}^\circ F}\right)$$

$$b = \textit{thickness of formwork or insulation (in.)}$$

$$k = \textit{conductivity of formwork or insulation}\left(\frac{Btu}{day\text{-}in.\text{-}^\circ F}\right)$$

$$R_{formwork} = R \textit{ value of formwork}\left(\frac{day\text{-}in.^2\text{-}^\circ F}{Btu}\right)$$

$$R_{insulation} = R \textit{ value of insulation}\left(\frac{day\text{-}in.^2\text{-}^\circ F}{Btu}\right)$$

(4) Foundation model. The foundation should be included in the heat transfer model to determine a realistic temperature distribution within the structure. The foundation should be no less than 10 ft in depth based on previous parametric studies (Truman, Petruska, and Ferhi 1992). Prior to performing the heat transfer analysis of the structure and foundation, a heat transfer analysis should be performed on the foundation for a time period of 1 year to determine the temperature distribution in the foundation for the start of concrete placement. The vertical size of elements in the foundation model should be determined using the equation A-1, but the horizontal size will be dictated by the size of the elements in the structure. The heat transfer analysis of the structure and foundation may include an interface element at the foundation-concrete interface. If an interface element is used, a gap conductance of 200 Btu-in./in.^{2}-day-°F should be specified.

(5) Time increments. The maximum time increments to be used in the heat transfer analysis are given in Table A-2. These same limits on increments are used in the stress analysis. The small increments at the early times are necessary to capture the large amounts of heat that are generated in very young concrete. The time increments specified in Table A-2 are for days after a lift of concrete has been placed. Exceeding the maximum time increments specified in Table A-2 is permissible, provided a parametric study is performed which demonstrates that results for both

the heat transfer and stress analyses are not significantly affected by exceeding the maximum.

e. Stress analysis.

(1) Gravity loads. Gravity loads (self weight of the structure) will be included in all NISA analyses. It is unnecessary to include formwork as a part of the stress analysis due to the method in which the gravity load of the concrete is applied at early times. In newly placed lifts, the concrete has not aged sufficiently to use element body forces to model gravity loads without causing excessive displacement and cracking. At these times in an analysis, gravity loading of the newly placed lift shall be applied as an equivalent uniform load acting on the top surface of the supporting lift. In locations where the newly placed lift spans a void in the supporting lift, the equivalent uniform load shall be applied to the surface at the bottom of the void. Application of the gravity load over a void in this manner is consistent with normal construction practice where formwork supports the new lift by transferring vertical loads to the floor of the void. Equivalent uniform loads should be removed and replaced with element body forces after the modulus of elasticity in the newly placed lift has aged to 1,000,000 psi. The time at which the modulus of elasticity reaches this limit may be determined from the modulus versus time curve obtained from material testing. The change in gravity loading can then be made during the nearest subsequent timestep shown in Table A-2.

(2) Foundation model. For soil or pile foundations, the foundation material should be included in the model using spring constants. For soil-founded structures, the soil can be replaced by springs which model the stiffness of the soil. For pile-founded structures, the springs should account for the stiffness of the soil and the piles, including any lateral stiffness that the piles provide. Failure to include the stiffness associated with the soil at nodes between the nodes where the pile stiffness is modeled will allow the concrete to develop excessive deformations between the piles at early times. If the results of an analysis are to be used in evaluating a pile design, then the soil stiffness should be removed after 30 days to allow the piles to carry the entire load. If the structure is rock founded, then the structural engineer may choose between modeling the foundation with continuum elements, developing vertical and lateral stiffness spring coefficients to model the rock properties, or using super elements to model a major portion of the foundation. The use of super elements (or substructuring) is a technique of modeling where a super element represents the stiffness of a large number of regular elements.

(3) Time increments. The maximum time increments to be used in a stress analysis should be the same as the heat transfer analysis and the increments are given in Table A-2. The small increments at the early times are necessary to capture the effects of creep, shrinkage, and the aging modulus of elasticity, since it is at the early times that these properties change the most.

(4) Smeared crack model. NISA is based on an interactive stress-strain cracking criterion as described in Annex 2 of Appendix A. The basis for the criterion is data from the slow load test. The aging modulus of elasticity makes the cracking criterion age-dependent. The ANACAP-U software checks calculated stresses and strains against the cracking criterion at each timestep. If the criterion is exceeded at any integration point (elements used in a NISA typically have four integration points for each rectangular element), a crack will be introduced perpendicular to the direction of maximum principal strain. If a crack is introduced, the constitutive matrix for the element is reformulated and a new stress state is developed based on zero stress perpendicular to the crack. The new constitutive matrix and stresses are then used for subsequent calculations until the crack closes. The cracks will close when placed in a compressive state, and the material will again be able to carry compressive loads. With this approach, the entire element matrix is affected if a crack is determined at any integration point. This is referred to as a smeared crack model, and it will provide information which indicates the depth and extent of cracking.

Table A-2
Maximum Time Increments Allowed in a NISA

Days after lift placed	0-2	2-5	5-15	15-35	35-100	100+
Maximum time increment (days)	0.25	0.5	1.0	2.0	5.0	10.0

A-6. Evaluation of Results

a. General. Current practice relies heavily on engineering judgement to evaluate the results of a NISA. The performance of a NISA is a means for assessing MCS's with regard to thermal loading and the potential for cracking. A NISA is not a linear analysis with factors of safety and allowables, but it is a prediction of actual response under extreme conditions. Controlling the ultimate response will require require adjustments to those structures with potential cracking problems. Adjustments might be made in construction procedures, materials, and/or geometric configuration to provide better ultimate performance. These adjustments will ensure a more reliable product.

b. Verification of input and data. The design team must use every available means to verify the correctness of the actual data and the input data for the NISA. NISA's require a considerable and widely varied set of structural, material, and thermal input parameters. This variety of parameters, some of which are unfamiliar to structural engineers, require the utmost care in verification of units and magnitude. General guidelines for input verification for finite element analyses are given in ETL 1110-2-332.

c. Verification of results. The design team should use any means available to help verify the validity of the results. Using the minimum specified parametric combinations provided in paragraph A-2, coupled with the experience and judgement of the structural engineer, an initial check of the results can be made on a qualitative basis. Exploring previously analyzed NISA structures and their results, performing a simple ambient condition analysis (no creep, shrinkage, aging modulus, or adiabatic temperature rise), and performing a simple gravity turn-on analysis (typical linear structural analysis) are all possible methods for providing confidence and a check on the validity of the structural model, effects of ambient temperature load, and aging material properties. Material property combination 1 (paragraph A-2) is to be used for education, verification, and validation regarding these parameters without performing exhaustive parameter studies. Extensive parameter studies have been performed in the past for several projects as outlined by Truman, Petruska, and Ferhi (1992) and Garner et al. (1992). Engineering judgment must be used in all cases since the effects of these parameters can produce results that are significantly different than the conventional linear, gravity turn-on analysis.

d. Cracking criteria.

(1) Model. The potential for cracking at any integration point is checked using an interactive stress-strain cracking criterion. The cracking criterion is not explicitly time dependent which is why an interactive stress-strain criterion is used. The time effects are accounted for through the age-dependent modulus as described in Annex 2, Appendix A. If the cracking criterion is violated, a crack will be introduced perpendicular to the direction of the maximum principal strain. If a crack is introduced, the constitutive matrix is reformulated within ABAQUS, and a new stress state is developed based on zero stress in the principal tensile strain direction. The new constitutive matrix and stresses are then used for subsequent calculations until another crack is indicated by the criterion or the crack closes. The cracks will close when placed in a compressive state, and the material will again be able to carry compressive loads. Depending on the severity of the crack, the shear resistance is reduced at the cracked integration points, but the crack will have limited shear resistance due to friction and aggregate interlock.

(2) Evaluation.

(a) Concrete cracking. The cracking criterion is yes, the material has cracked, or no, it has not. This yes/no crack prediction is necessary and correct when finding the ultimate response of the structure, but it is not very useful in predicting reliability or potential for cracking. Therefore, the ANACAP-U subroutine provides a percentage of the cracking criterion to evaluate the potential for cracking. A percentage approaching 100 indicates an increasing possibility of cracking. Any structure with a NISA that indicates cracking should be evaluated for the severity of the consequences of the predicted cracks. If the consequences are deemed detrimental with respect to safety or economics, the structure should be redesigned. Possibilities for redesign include, but are not limited to, the use of additional reinforcement, the revision of construction procedures, and/or the modification of the material constituents to alleviate or control the cracking.

(b) Reinforcing. Resulting stresses in the reinforcing bars should be monitored, reported, and

compared to the yield strength of the reinforcing. If the yield strength of the reinforcing is exceeded, then the structure should be reevaluated with changes to other parameters to improve performance.

(3) Winter protection. The effects of cold fronts may cause significant cracking within a MCS and should be considered when evaluating the MCS. This winter protection evaluation is required mainly to assess the need, duration, and R-value for possible insulation of the structure. Cold fronts have not been specifically required in the NISA studies due to their sporadic and unpredictable occurrences. Yet, they do occur and are commonly the cause for cracking of structures while under construction. Their unpredictability in magnitude, occurrence, and duration create significant complexities in computer modeling of their effects and behavior. A reasonable approximation without specific analysis is to locate all uninsulated regions of the MCS that have a cracking potential greater than 80 percent during those periods of construction when cold fronts are possible and would be considered detrimental to the structure. A structure with a NISA that exceeds the 80-percent cracking potential should be insulated or other modifications should be made to reduce the risk of cracking during a cold front. Insulation should be used whenever the cracking potential exceeds 80 percent during that portion of the year when cold fronts are possible. The evaluation of R-values for insulation purposes may require an additional NISA(s) to be performed. The design team must use the NISA results coupled with experience and engineering judgement to develop the final requirements for insulation during construction.

(4) Practical hints. Regions of potential cracking are project dependent due to the fact that the structure, the climate, materials, and construction procedures are all typically site specific. If cracking should occur in a structure, various measures can be taken to reduce or eliminate cracking. Presented below are some possible areas to consider when efforts are being made to improve the structure's behavior due to the presence of cracking. Solutions for reducing cracking will vary based on the mechanism causing the cracking and therefore careful consideration should be given to any items used prior to their implementation.

(a) High thermal gradients. If cracking is created due to a high thermal gradient, changes for reducing this gradient may be made by lowering the placing temperature or by adding insulation. These are relatively simple changes to make both in the analysis and in the specifications, although both changes will increase construction costs. Changes in the analysis will require a change in the initially specified temperatures in the heat transfer analysis for a change in placing temperature, and a change in insulation will require the value of the film coefficients to be revised. An additional item to consider for reducing high thermal gradients is to place voids in the areas of the structure where the concrete may not be required for structural considerations. This will reduce the amount of heat generated which may reduce the thermal gradient. In addition, this alternative will remove concrete and may be a savings instead of a cost.

(b) Cracking at corners. If cracking occurs at corners of openings and it is desired to limit these cracks, but not necessarily eliminate them, then additional reinforcing in these areas should be considered. Typically, reinforcing placed at a 45-deg angle at the corner of the opening is the most beneficial for controlling cracking. This will require adding reinforcing elements through the ABAQUS *REBAR option. It is also recommended that if reinforcing is to be included in an analysis, the ANAGEN preprocessing software (ANATECH Research Corp. 1992) be used in developing the model. Use of ANAGEN will significantly decrease the difficulty of including reinforcing in the model, particularly for sloping bars.

e. Pile reactions. An evaluation of the pile reactions should be performed to determine the effects of construction procedure, thermal loads, and aging material properties coupled with service loads on the load distribution for the piles. This should be a qualitative evaluation where minor pile overload or overstressing should be of little concern.

f. Output interpretation. This section is intended to give insight into the various methods that have proven useful in interpretation of analysis results and not to provide a rigid framework of steps to follow. The structural engineer must sufficiently process results to comprehend the behavior of the structure and provide the necessary data (plots, diagrams, tables, etc.) to support conclusions based on this understanding.

(1) Contour plots. Contour plots of temperature, stress, net strain, and crack potential are useful in selecting zones in the structure for more detailed

investigation. Contours should be relatively smooth within a lift and should not abruptly change directions. All contour plots should be checked to ensure they reflect symmetry where a symmetrical boundary condition has been applied to the model. Plotting software should use results at element integration points, not nodal results averaged from locations in different lifts. Although each lift consists of concrete, they are in essence different materials, since the age of the concrete is different from one lift to the next. Therefore, averaged results tend to smooth contours and lessen their magnitudes.

(a) Stress/strain contours. Contours of stresses and strains in the global coordinate directions along with contours of principal stresses and strains should be used in formulating and supporting conclusions drawn about the response of the structure. Contours near piles, lift interfaces, and reentrant corners typically lack smoothness due to abrupt changes in stiffness in nearby materials and stress concentrations. Such abrupt changes may indicate errors in input or modeling, or areas where the FE mesh should be refined. Mesh refinement should be considered only if contours lack smoothness in critical areas. Due to changing orientation, principal stress and strain plots typically are not as smooth as stress and strain plots in the x, y, or z directions. A contour plot of maximum principal stress, s11, is shown in Figure A-3. The ABAQUS computer program outputs and plots total strain which includes strain due to free expansion, not just the net strain (the portion of the total strain that produces stress). Strains due to free thermal expansion do not produce stress or contribute to cracking of concrete and should not be included in strain plots. Therefore, total strains are not useful in interpreting results, and the strain plotting capabilities of ABAQUS should not be used. Net strain contour plots can be obtained by using the ANACAP-U software (ANATECH Research Corp 1992).

(b) Temperature contours. Temperature contours should be smooth throughout a lift and across lift interfaces. Temperature contours should never abruptly intersect free surfaces of the model where film coefficients are applied, except for locations where a very low film coefficient is used to model an enclosed void. This indicates the application of an incorrect thermal boundary condition. A temperature contour is shown in Figure A-4.

(c) Crack potential contours. This type of plot, Figure A-5, is only available through the use of ANACAP-U and is used in conjunction with crack location plots. Contours reflect the largest percent of the cracking criteria reached at a specified time for all principal strain directions. This type of plot is useful in assessing the potential for cracking in the structure for a given loading and material property combination. These plots are also useful for the evaluation of insulation requirements for winter protection. Once a crack has formed, the largest percent of the cracking criteria for the remaining uncracked principal strain directions is plotted in subsequent contours for locations along the crack. This typically results in a drastic change of crack potential in subsequent contours for locations where a crack has previously formed. Therefore, crack potential contour plots must be used in conjunction with crack location plots to correctly assess the cracking potential of the structure.

(2) Time-history plots. Time-history plots of temperature, stress, strain, and principal stress results at a single location or multiple points across a section of significance are useful in showing the response of that location throughout the time of the analysis. These are useful in determining the critical material property combination when multiple analyses are performed. A time-history plot of horizontal stress is shown in Figure A-6. To assist reviewers and persons unfamiliar with the model, a locator section is provided to show the location in the model where the results are presented. Selection of locations for presentation of time-history results may be determined from contour plots, from the determination of locations of maximum values of results, or from locations of particular interest. These may be places where similar structures have experienced problems, places where previous NISA's have presented results, or places which help explain the overall response of the structure.

(3) Section plots. Plots of results (i.e., stress, temperature, net strain) across a specified section or location at a specific time are useful in determining the behavior of the section or location. Stress results, as seen in Figure A-7, typically show distortions at lift interfaces. These distortions arise from the different load history and different material properties resulting from different ages of concrete in adjacent

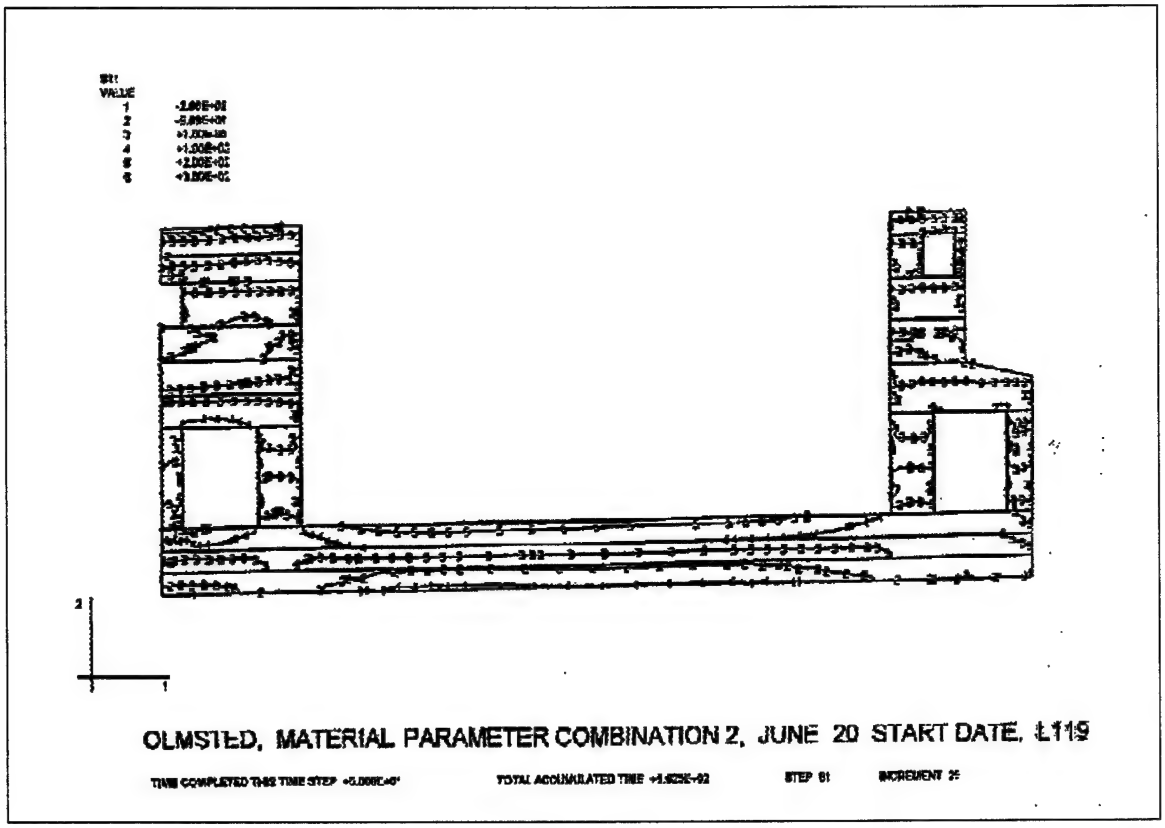

Figure A-3. Principal stress contour example

lifts. Determination of the maximum value of a specific result (i.e., stress, strain) and its time of occurrence is useful in determining which section or location to plot and the corresponding time.

(4) Displaced shapes. Displaced shape plots, Figure A-8, can be used to see the overall response of the structure due to the applied load. Due to the methods used to implement incremental construction in ABAQUS, displaced shape plots typically show model induced distortions at lift interfaces. These distortions are plotting discontinuities resulting from the display of total nodal displacements in the newly initialized lift relative to their displaced locations instead of their original undisplaced locations. This misapplication of displacement is for ease of plotting and occurs only in plotting of the displaced shape. Nodal displacements are handled correctly in the analysis during each timestep by ABAQUS.

(5) Crack location plots. This type of plot, Figure A-9, is available only through the use of ANACAP-U (ANATECH Research Corp 1992) and shows locations of all cracks in the structure at a specified time. When displayed at a sufficiently large scale, crack status (open or closed) may be observed. For 2-D analyses, open cracks are denoted with double lines, while closed cracks are denoted with single lines. For 3-D analyses, open cracks are denoted with two concentric circles, while closed cracks are denoted with single circles. Typically, a crack location plot is developed for the last timestep in an analysis. This can show the extent of cracking throughout the structure and whether the cracks are open or closed at this time. Using this information, other crack plots can be developed for times when cracks initially form or for use in tracking further crack development.

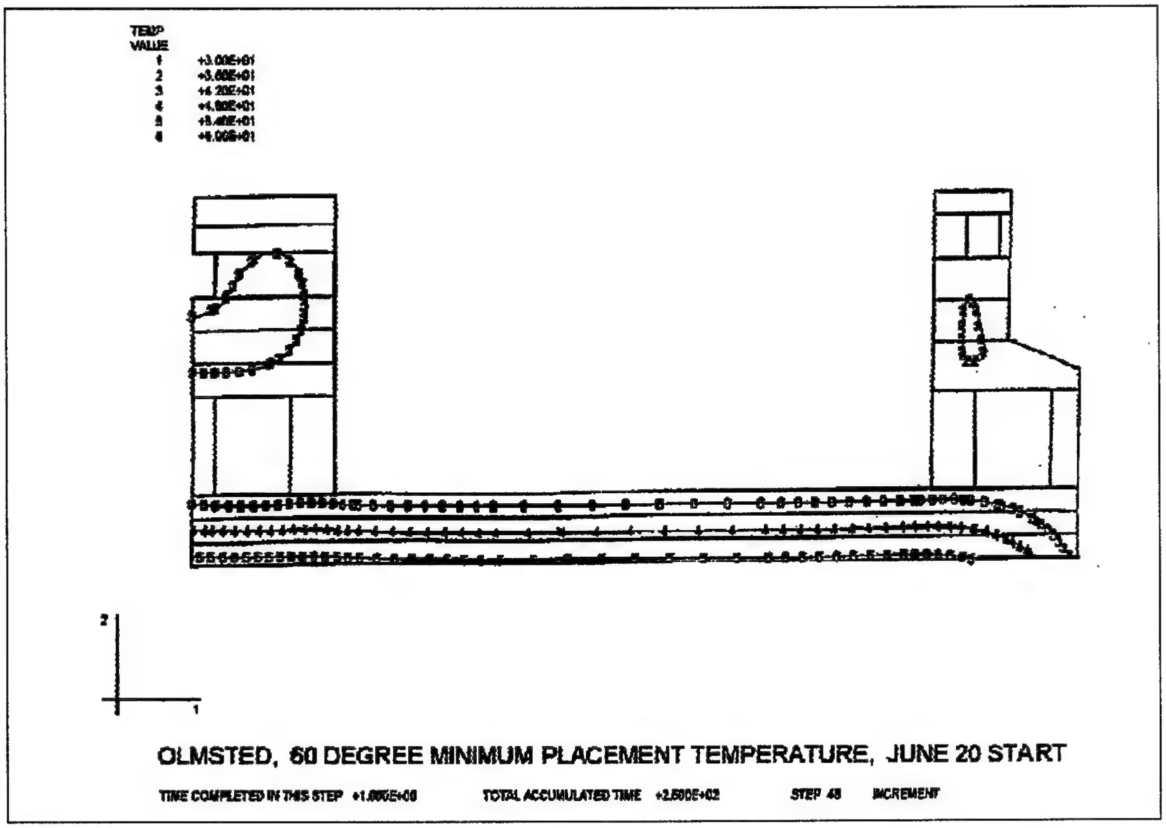

Figure A-4. Temperature contour plot example

A-7. Report

Results from a NISA study will be presented in a separate design memorandum (DM) entitled "Nonlinear, Incremental Structural Analysis."

a. Statement of objectives. The DM should document the benefits from performing a NISA study including how the performance of the structure was improved and the cost savings that resulted. When discussing cost savings, a comparison of the costs before and after the NISA study should be provided. Development of the projected cost savings should be done in close coordination with the cost engineer.

b. Report requirements. When reporting the results of a NISA study, the following items should be included in the DM in the order shown:

(1) Objectives. The objectives stated should be consistent with objectives identified in paragraph A-1*a*.

(2) Initial conditions. All construction parameters which were identified as the initial conditions of the NISA study should be described in this section of the DM as well as the reasons for their selection. Included in this discussion will be items such as the start time, the lift heights, the placing temperature, and insulation requirements.

(3) Final design. This section should be a description of the final parameters selected for use in the development of the plans and specifications of the project. These items will be the same items that are discussed in the initial conditions.

(4) Analysis description. A description of the various modeling parameters used in the analyses should be included based on the items listed:

(a) The structure geometry, with all appropriate dimensions

(b) Material properties

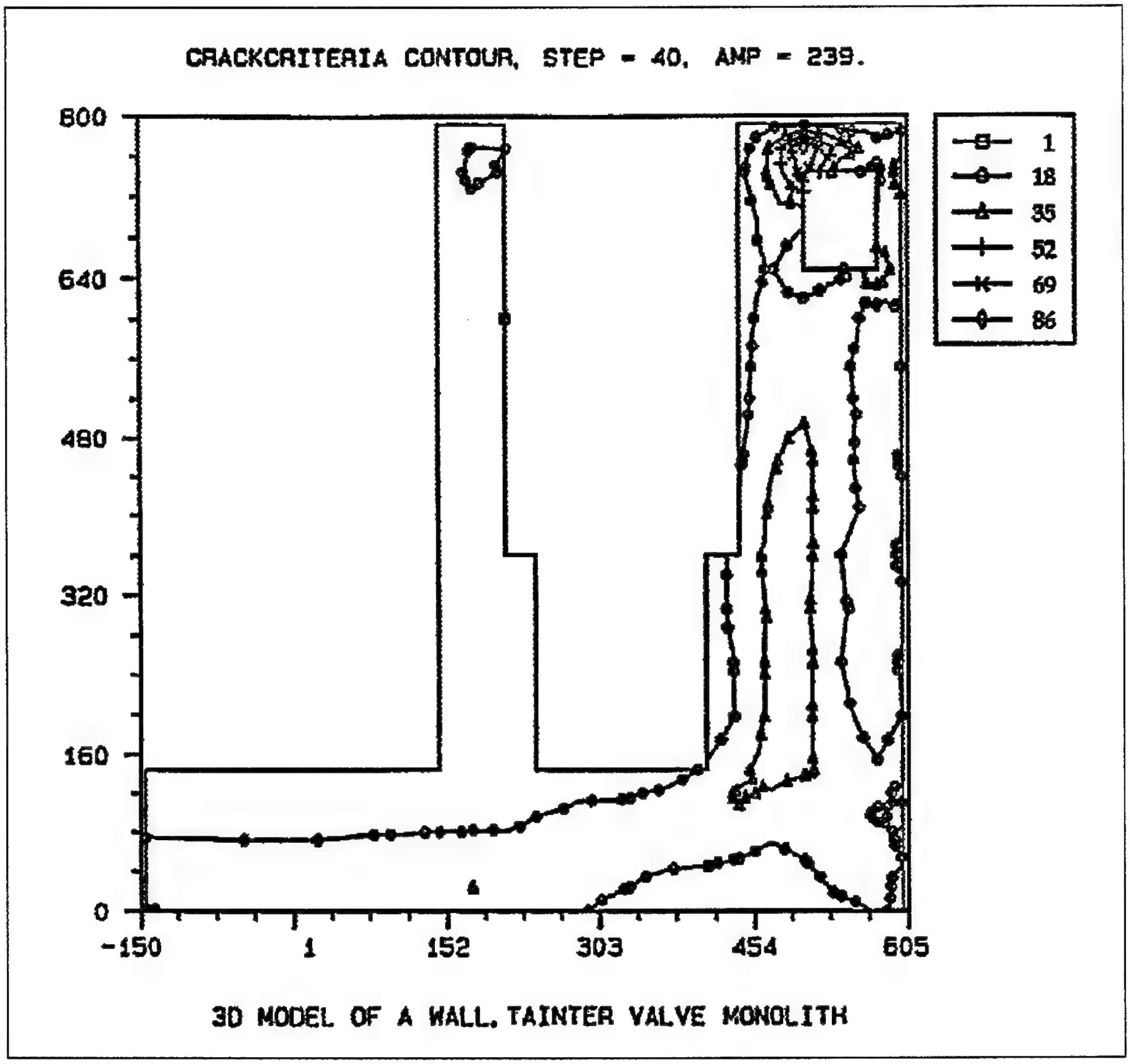

Figure A-5. Crack potential contour plot example

(c) Film coefficients

(d) Parametric combinations

(e) Service loads

(f) Boundary conditions

(g) Ambient conditions

(h) Concrete placing temperatures

(i) Foundation temperature distribution

(5) Evaluation. An evaluation of the NISA should be included which describes:

(a) Verification of input

(b) Verification of results

(c) Cracking potential

(d) Acceptability of cracking

(e) Corrective measures

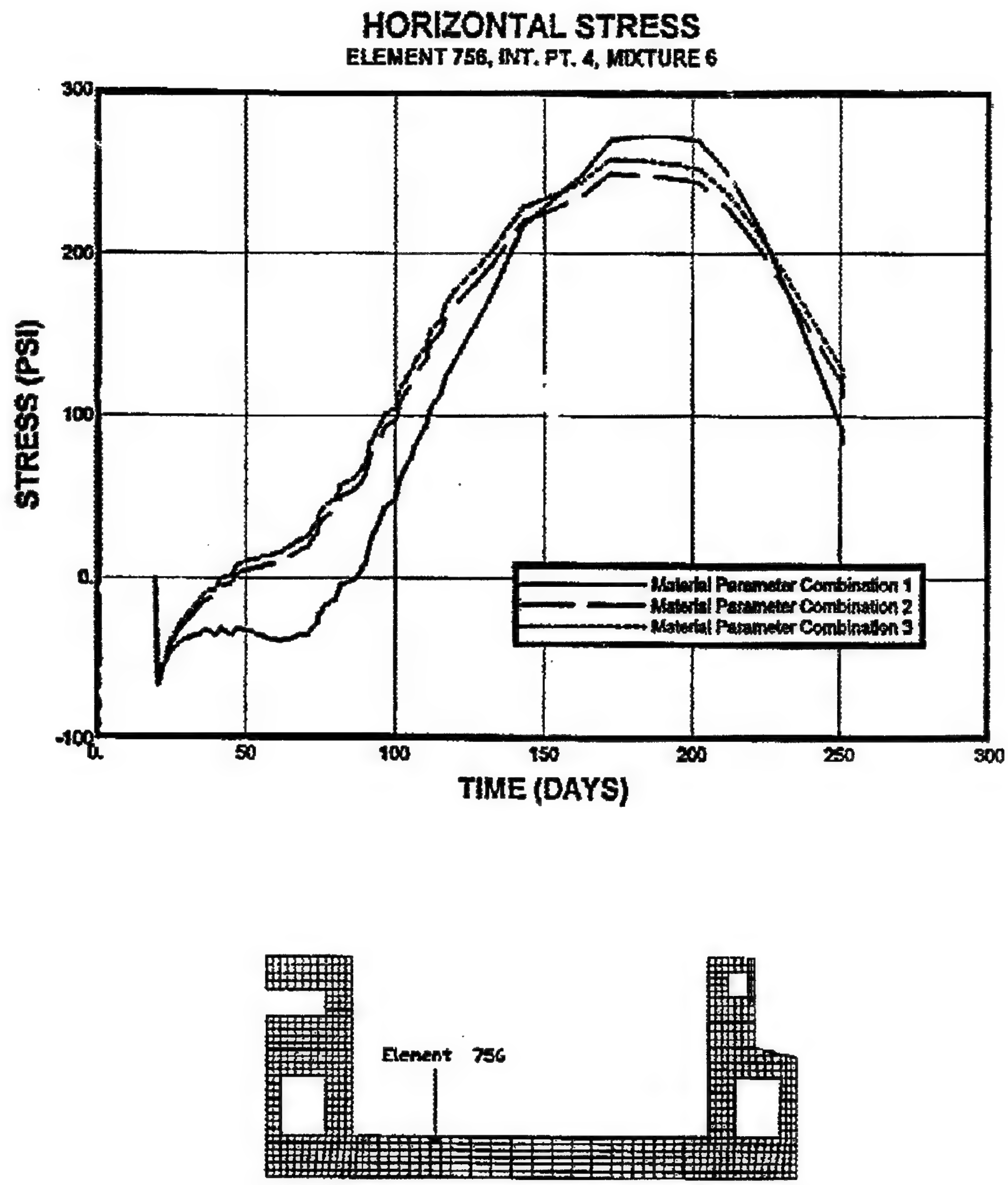

Figure A-6. Stress time-history plot example

(6) Conclusions. The conclusion should discuss the major points which will support the objectives stated, whether that be for improved structural performance or cost savings.

c. Appendix to the DM. An appendix to the DM should be included which provides detailed discussion of parameters and results of the NISA study. The content and layout of this appendix should follow the guidelines presented in Annex 5 of this appendix.

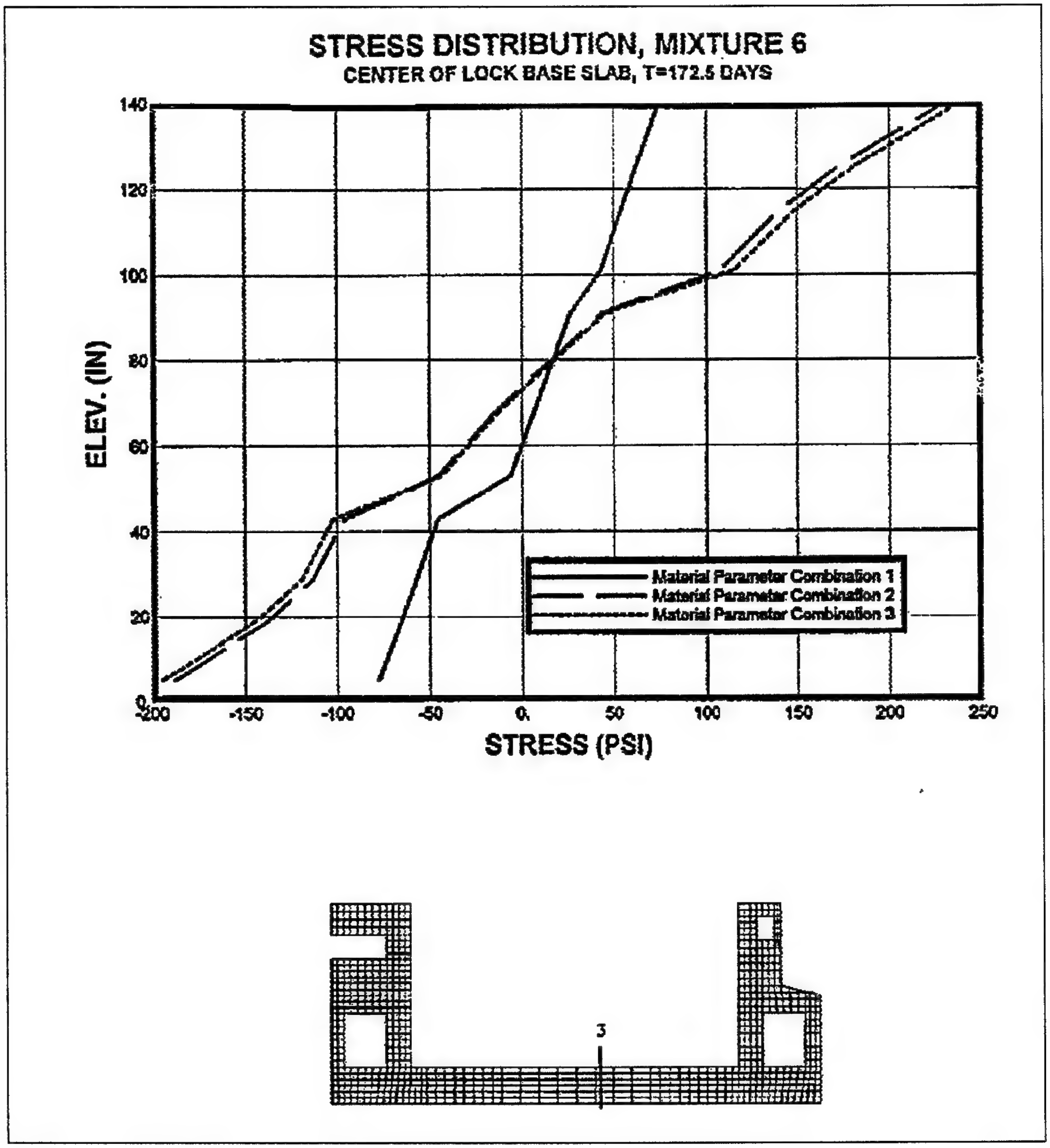

Figure A-7. Section plot example

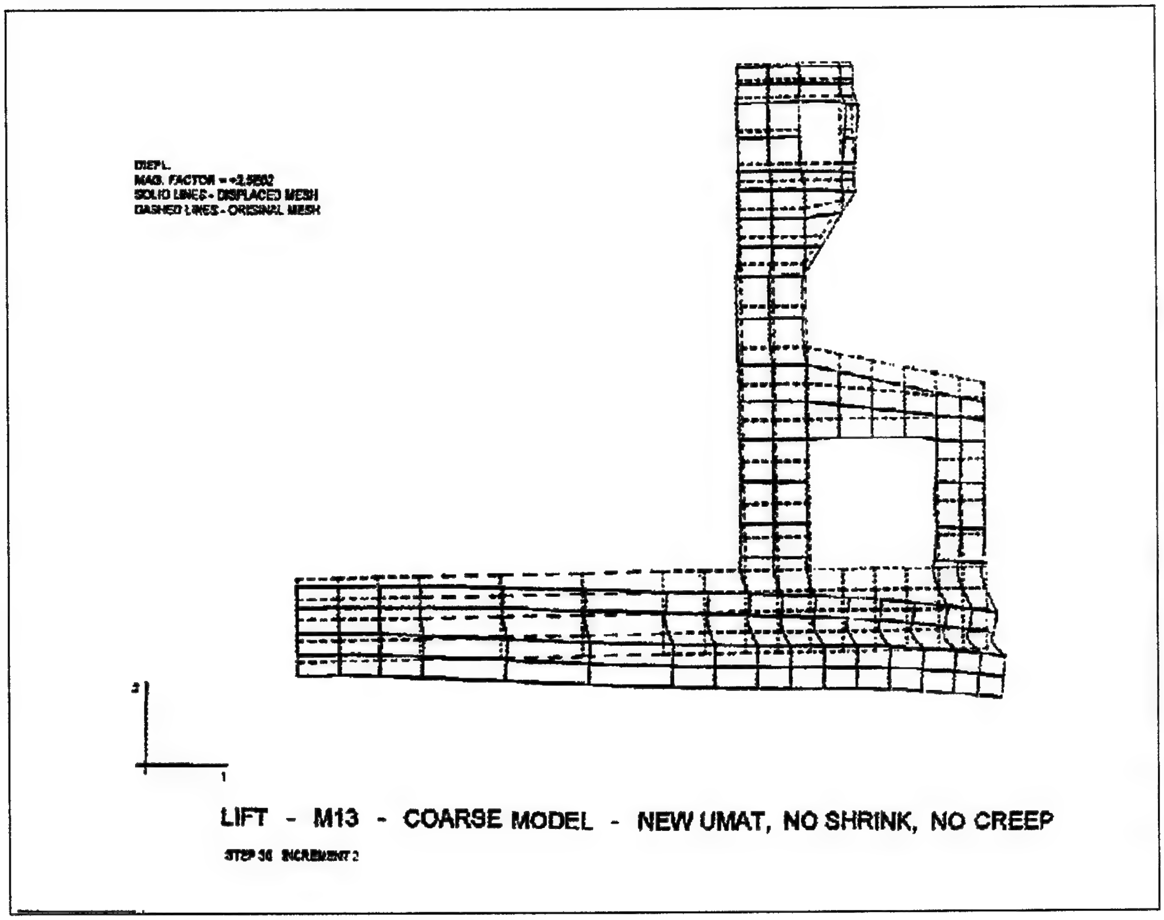

Figure A-8. Displaced shape plot example

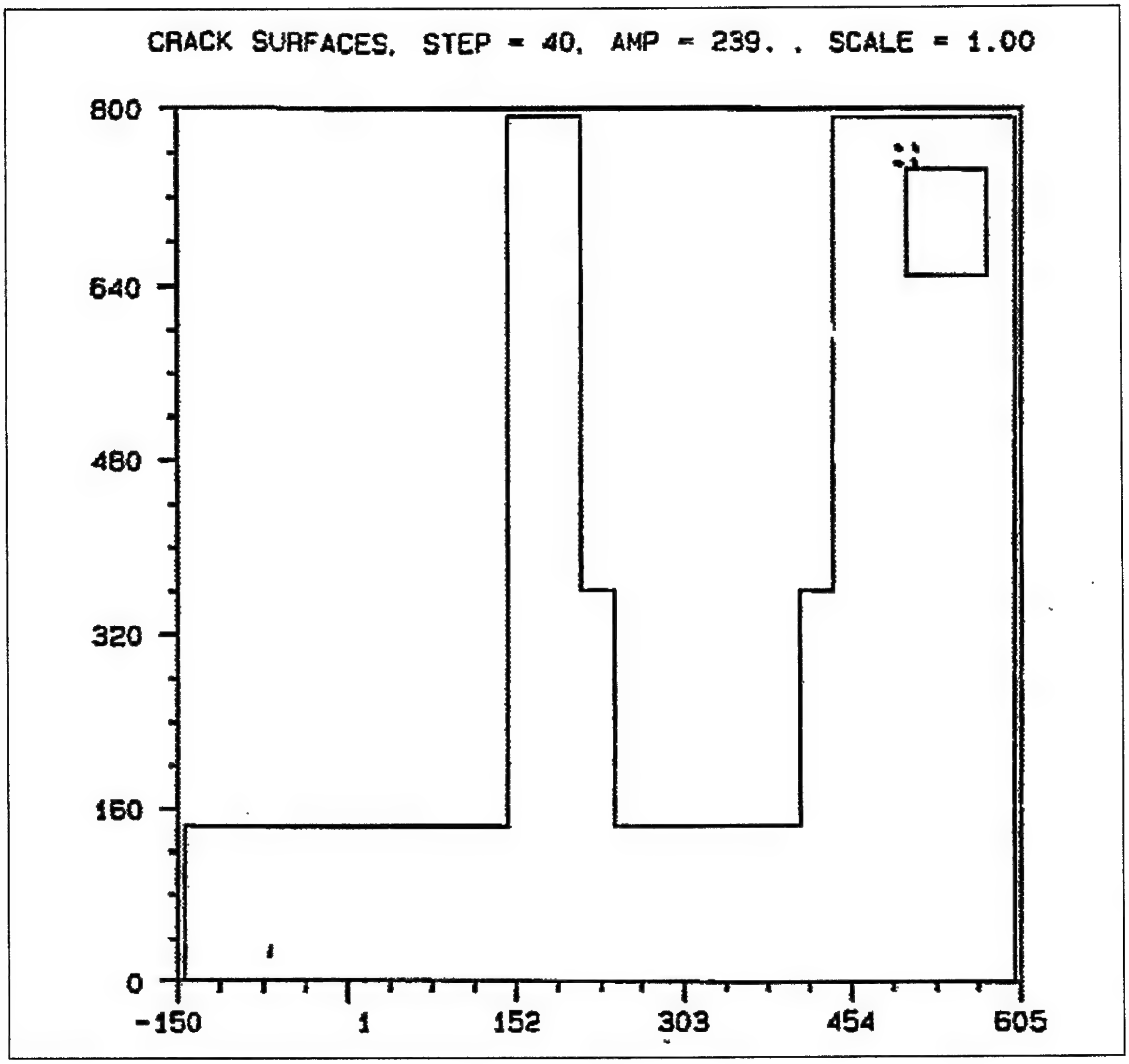

Figure A-9. Cracked location plot example

A-8. Required References

a. ER 1110-2-1150, Engineering and Design for Civil Works Projects.

b. EM 1110-2-1906, Laboratory Soils Testing.

c. EM 1110-2-2000, Standard Practice for Concrete.

d. EM 1110-2-2906, Design of Pile Foundations.

e. ETL 1110-2-332, Modeling of Structures of Linear Elastic Finite Element Analysis.

f. American Concrete Institute, Committee 116. 1992. "Cement and Concrete Terminology," *ACI Manual of Concrete Practice, Part 1*, Detroit, MI.

g. American Concrete Institute, Committee 207. 1992a. "Mass Concrete for Dams and Other Massive Structures," ACI 207-1R, *ACI Manual of Concrete Practice, Part 1,* Detroit, MI.

h. ACI Committee 207. 1992b. "Effect of Restraint, Volume Change, and Reinforcement of Cracking of Massive Concrete," ACI 207-2R, *ACI Manual of Concrete Practice, Part 1,* Detroit, MI.

i. American Society of Heating, Refrigerating and Air-Conditioning Engineers. 1977. *ASHRAE Handbook and Product Directory - 1977 Fundamentals*, New York, NY.

j. American Society for Testing and Materials. 1992. *1992 Annual Book of the ASTM Standards*, Philadelphia, PA.

(1) Designation D 3148-86, "Test Method for Elastic Moduli of Intact Rock Core Specimens in Uniaxial Compression."

(2) Designation D 4535-85, "Test Method for Measurement of the Thermal Expansion of Rock Using a Dilatometer."

(3) Designation D 1586-84, "Method for Penetration Test and Split-barrel Sampling of Soils."

k. ANATECH Research Corp. 1992. *ANACAP-U, ANATECH Concrete Analysis Package, Version 92-2.2, User's Manual,* San Diego, CA.

l. Fehl, B. D., and Merrill, C. A. "Use of Reinforcement in a Nonlinear, Incremental Structural Analysis" (technical report in preparation), U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

m. Garner, S. B., and Hammons, M. I. 1991. "Development and Implementation of a Time-dependent Material Model for Concrete," Technical Report SL 91-7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

n. Garner, S. B., Bombich, A. A., Norman, C. D., Merrill, C., Fehl, B., and Jones, H. W. (1992). "Nonlinear, Incremental Structural Analysis of Olmsted Locks and Dams - Volume I, Main Text," Technical Report SL-92-28, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

o. Hammons, M. I., Neeley, B. D., Alexander, A. M., Bombich, A. A., and Garner, S. B. 1991. "Concrete Mixture Selection and Characterization Study Olmsted Locks and Dam, Ohio River," Technical Report SL-91-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

p. Hibbitt, Karlsson, and Sorensen. 1989. *ABAQUS User's Manual, Version 4.9.*, Providence, RI.

q. Hunt, R. E. 1986. *Geotechnical Engineering Techniques and Practices,* McGraw-Hill, New York.

r. Jones, H. W., and Foster, J. "Finite Element Method Guidance for the Analysis of Gravity Dam Structures, Foundation Effects - Phase Ib" (technical report in preparation), U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

s. Jumikis, A. R. 1977. *Thermal Geotechnics,* Rutgers University Press, New Brunswick, NJ.

t. Kersten, M.S. 1949. *Laboratory Research for the Determination of the Thermal Properties of*

Soils, Engineering Experiment Station, University of Minnesota, Minneapolis, MN.

u. Neville, A. M. 1981. *Properties of Concrete*, Wiley, New York.

v. Smith, D. M. 1991. "Mechanical Properties of Mass Concrete at Early Ages," Technical Report SL-91-14, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

w. Truman, K. Z., Petruska, D., and Ferhi, A. 1992. "Evaluation of Thermal and Incremental Construction Effects for Monoliths AL-3 and AL-5 of the Melvin Price Locks and Dams," Contract Report ITL-92-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

x. U.S. Army Engineer Waterways Experiment Station. 1949. *Handbook for Concrete and Cement,* Vicksburg, MS.

(1) Designation CRD C 38-73, "Method of Test for Temperature Rise in Concrete."

(2) Designation CRD C 124-73, "Method of Test for Specific Heat Aggregates, Concrete, and other Materials (Method of Mixtures)."

(3) Designation CRD C 36-73, "Method of Test for Thermal Diffusivity of Concrete."

(4) Designation CRD C 37-73, "Method of Test for Thermal Diffusivity of Mass Concrete."

(5) Designation CRD C 19-89, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression."

(6) Designation CRD C 44-63, "Method of Calculation of Thermal Conductivity of Concrete."

(7) Designation CRD C 54-89, "Standard Test Method for Creep of Concrete in Compression."

(8) Designation CRD C 39-81, "Test Method for Coefficient of Linear Thermal Expansion of Concrete."

(9) Designation CRD C 71-80, "Standard Test Method for Ultimate Tensile Strain Capacity of Concrete."

(10) Designation CRD C 23-91, "Standard Test Method for Specific Gravity, Absorption and Voids in Hardened Concrete."

y. U.S. Army Engineer Waterways Experiment Station. 1990. *Rock Testing Handbook,* Vicksburg, MS.

z. Will, K. M. 1987. "Procedure for Static Analysis of Gravity Dams Using the Finite Element Method - Phase Ia," Technical Report ITL-87-8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

ANNEX 1: NONLINEAR, INCREMENTAL STRUCTURAL ANALYSIS (NISA) DURING FEASIBILITY PHASE

A1-1. Purpose

A NISA is usually performed during preconstruction engineering and design (PED). However, if an unprecedented structural configuration is being proposed, it may be necessary to perform a NISA during the feasibility phase to identify requirements for unusual construction procedures which will significantly affect project costs. The design team must determine the need for a NISA as early as possible during the feasibility phase. This is necessary to allow results of the NISA to be incorporated into the Feasibility Report.

A1-2. Scope of Analysis

A NISA during feasibility studies is nearly identical to a NISA during PED. However, during feasibility studies the objective is limited to determining significant impacts on project cost due to special construction procedures. Approximate results may be adequate to define the magnitude of the cost impact. Therefore, the scope of the analysis may be simplified. This should not usually require numerous runs with multiple parameter combinations. This annex identifies the reduced requirements for NISA during feasibility studies.

A1-3. Parametric Combinations

Analysis should include only material parameter combinations 1 and 3. Combination 3 is usually the set of properties which produces the critical results. Results from combination 1 should be available for comparison with combination 3 to help evaluate the sensitivity of results to effects of creep and shrinkage. This knowledge may be necessary for selection of appropriate contingencies in the baseline cost estimate. Two different construction start dates should be analyzed, using extreme ambient temperature conditions. Other parametric studies may be appropriate, but the number should be limited.

A1-4. Material Properties

Test results for concrete mixtures will probably not be available for performing a NISA during feasibility. Material properties should be selected by the design team based on previous test results from other projects and adjusted for probable conditions on the new project. Properties should be consistent with a single concrete mixture. Due to the uncertainty about project specific materials, properties selected for use should include a bandwidth of ±30 percent from the expected value. This applies to values for creep, shrinkage, and adiabatic temperature rise.

A1-5. Evaluation of Results

Results should be evaluated in terms of acceptable cracking or cracking potential. The purpose of the analysis is to determine whether special, costly construction procedures are required. Therefore, there is no specific evaluation standard for a NISA during feasibility. If the analysis shows minor cracking or low cracking potential, normal construction procedures are likely to suffice and usual cost estimates and contingencies are satisfactory. If cracking exists or cracking potentials are high, higher contingencies should be used for concrete costs to represent undetermined special procedures. If cracking is severe, additional NISA investigation may be needed to identify the type and magnitude of design or construction procedure changes needed to provide acceptable performance.

A1-6. Report

The NISA study and results should be described in a section of the engineering appendix to the Feasibility Report and not in a separate report. The information should include input data such as geometry, finite element model, material properties, parameter combinations, loads, ambient temperature, film coefficients, etc. Plots of results should be included to illustrate

the behavior of the structure. These plots should include temperature, stress and crack potential contours at critical times, plus temperature and stress time histories at critical locations. There should also be a narrative interpretation of the results. This should explain any cracking or the potential for cracking, whether it is acceptable, what special design or construction procedure changes might be required, and what cost adjustment was made because of these changes.

ANNEX 2: CRACKING CRITERION

A2-1. General

The cracking criterion is a stress-strain interactive criterion. It is made time dependent through the use of a linear relationship between cracking stress and cracking strain which is dependent on the aging modulus. This criterion is illustrated in Figure A2-1. If the principal stresses and their respective principal strains, when plotted on Figure A2-1, are within the triangle enclosed by the failure surface and the two axes, no cracking occurs, and the cracking potential is calculated. If the point of principal stress versus principal strain lies outside the triangle, the concrete has cracked. If the system is cracked, the constitutive matrix, stress state, nodal forces, and stiffness matrix are adjusted prior to continuation of the analysis.

A2-2. Failure Surface Generation

The failure surface is a function of the slow load fracture stress, σ_s, the slow load fracture strain, ε_s, and the aging modulus at the time of fracture, $E_s(t)$. The strain axis intercept is determined as:

$$\varepsilon_f = \varepsilon_s + \frac{\sigma_s}{E_s(t)} \tag{A2-1}$$

as shown in Figure A2-1. This intercept value remains constant for the entire NISA and is a prediction of the concrete cracking strain. ABAQUS input data requires the user to input a cracking strain of:

$$\varepsilon_{input} = \frac{1}{2}\varepsilon_f = \frac{1}{2}\left(\varepsilon_s + \frac{\sigma_s}{E_s(t)}\right) \tag{A2-2}$$

All of these data should be obtained from the slow load test. The factor of 1/2 is a function of the input need by ANACAP-U to generate the correct strain axis intercept within the subroutine used for checking the cracking criterion. Since the strain intercept remains constant, the time dependency is related to the time variation of the aging modulus for the region of the structure being evaluated for cracking. This concept is illustrated in Figure A2-2. The stress axis intercept for a given age, t_i, is determined as:

$$\sigma_{f,i} = \varepsilon_f E(t_i) \tag{A2-3}$$

Figure A2-2 shows three different failure surfaces for the concrete ages of t_1, t_2, and t_3.

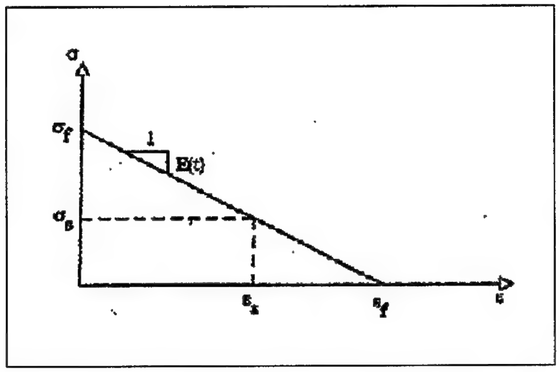

Figure A2-1. Cracking failure surface and ε_f generation from the slow load fracture data

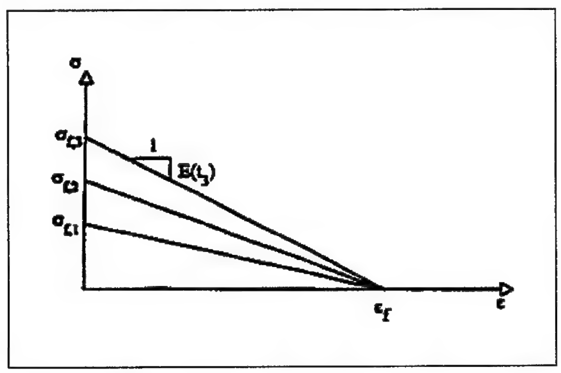

Figure A2-2. Computer generated, time-dependent (aging modulus) cracking failure surfaces

A2-3. Cracking Potential

Cracking potential is a quantitative measure of the imminence of exceeding the cracking criteria. It is equivalent to the ratio of l_1 to the total length ($l_1 + l_2$), as shown in Figure A2-3, where l_1 is the distance from the origin to the point (ε, σ) which reflects the actual principal stress and strain at a point in the structure. The value ($l_1 + l_2$) is the length of the line from the origin to the failure surface which passes through (ε, σ). The cracking potential is an indicator of how near the current stress-strain state is to the cracking surface.

A2-4. Computerized Procedure

The following is a brief step-by-step account of how the cracking model operates within the code.

a. Plot the point represented by the principal stresses σ_1 and σ_2 and their respective principal strains ε_1 and ε_2. Check if these points are inside or outside the surface.

b. If inside the surface, no cracking occurs. The cracking potential is calculated, and the next integration point is checked.

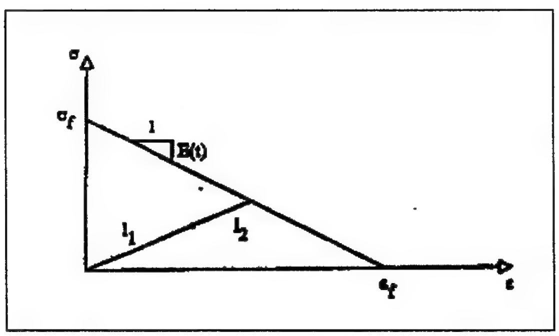

Figure A2-3. Cracking potential generation for a specific cracking failure surface

c. If on or outside the surface, introduce a crack perpendicular to the direction of the maximum principal strain.

d. In the direction perpendicular to the crack, the stress must then be set to zero, and the other stresses must be modified to reflect that change.

e. The stiffness matrix must then be modified to reflect zero load carrying capabilities in that direction until the crack closes and enters a compressive state.

f. If the material enters a compressive state, the crack is assumed to have closed and 100 percent of the compressive stiffness is reinstated in the direction perpendicular to the crack. Once the material is placed in a tensile state again, the crack and a zero stress state is reintroduced at this location.

A2-5. References

a. Garner, S. B., Bombich, A. A., Norman, C. D., Merrill, C., Fehl, B., and Jones, H. W. 1992. "Nonlinear, Incremental Structural Analysis of Olmsted Locks and Dams - Volume I, Main Text," Technical Report SL-92-28, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

b. Truman, K. Z., Petruska, D., and Ferhi, A. 1992. "Evaluation of Thermal and Incremental Construction Effects for Monoliths AL-3 and AL-5 of the Melvin Price Locks and Dams," Contract Report ITL-92-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

ANNEX 3: HEAT GENERATION SUBROUTINES

A3-1. User Subroutines

As discussed in the text, there are two user subroutines available for modeling heat generation in the concrete due to the heat of hydration. These two subroutines are DFLUX and HETVAL. A listing of each subroutine is provided with comments discussing various portions of the program. Comments which are for the purpose of this appendix only will be placed in double quotations. Please note that these subroutines were developed for use with version 4.9 of ABAQUS and may need to be modified for later ABAQUS versions.

***** USER SUBROUTINE DFLUX *****

```
      SUBROUTINE DFLUX(FLUX,TEMP,KSTEP,KINC,TIME,NOEL,NPT,COORDS,
                                    and JLTYP)
      IMPLICIT REAL*8 (A-H,O-Z)
C***************************************************************************************
C
C  VERSION 2.0
C  THE ADIABATIC CURVE IN THIS VERSION OF DFLUX IS BASED ON THE
C  ORIGINAL CURVE USED FOR L&D26.  UNITS IN THE T ARRAY ARE HOURS.
C  UNITS IN THE HEAT ARRAY ARE BTU/(LB-IN**3)
C
C  NQ IS THE NUMBER OF POINTS IN ARRAYS T & Q.  ENTIME IS THE ENDTIME
C  FOR DFLUX.   STTIME GIVES THE START TIMES FOR ELEMENTS IN HOURS.
C  THE DIMENSION OF STTIME MUST BE AS LARGE AS THE NUMBER OF ELEMENTS.
C  YOU MUST CHANGE THE VALUES IN STTIME TO CONFORM TO YOUR PROBLEM.
C  FOR INSTANCE, IF THE FIRST POUR IS MODELED USING 50 ELEMENTS,
C  50*0.0 WOULD START DFLUX AT TIME 0 FOR THE FIRST 50 ELEMENTS.
C
C***************************************************************************************
```

"The array COORDS is simply for the coordinates, Q and T are for the arrays given below and PROP is an array for the density and specific heat as given on the DATA PROP card"

```
      DIMENSION COORDS(3),Q(20),T(20),PROP(2)
```

"STTIME is defined below."

```
      COMMON /ELDEF/ STTIME(736)
      DATA PROP/.08681,.21/
      DATA ENTIME/648.1/
      DATA NQ/20/
```

"Array T is the time associated with each heat flux given in array Q"

```
      DATA T/.25,.5,.75,1.,1.25,1.5,1.75,2.,
     $       2.5,3.,3.5,4.,6.,7.,8.,
     $       9.,10.0,13.,15.,27./
```

```
      DATA Q/0.00716817,0.01285477,0.01651029,0.01342255,0.00867982,
     $        0.00579574,.00414259,0.00369022,0.00264052,0.00238157,
     $        0.00164695,0.00158670,0.00108267,0.00083101,0.00076965,
     $        0.00067882,0.00051608,0.00057410,0.00043135,0.00023181/
```

"The card which elements are included into the model at which time. In this case, elements up through element 544 are included in the model at time 0.0. The next 96 elements are not included for 10 more days and the 96 elements after that are not included until 20 days later. This arrangement is good only for elements that are sequentially ordered in the placement schedule."

```
      DATA STTIME/544*0.,96*10.,96*20./

C
C   **************
C  ENTIME = END OF RELATIVE HEAT GENERATION TIME + SMALL TOLERANCE
C
C  NQ     = NO. OF HEAT GENERATION RATE POINTS
C
C  T      = RELATIVE HEAT GENERATION TIME POINTS
C
C  Q      = HEAT GENERATION POINT
C
C STTIME  = VECTOR CONTAINING PLACEMENT TIME FOR EACH ELEMENT
C
C  FLUX   = HEAT GENERATION RATE RETURNED TO PROGRAM
C
C
C ********
```

"TREL is the relative time in the analysis for each lift."

```
      TREL = TIME - STTIME(NOEL)
      END = ENTIME
      IF( TREL.GT.0.0.AND.TREL.LT.END ) GO TO 10
      FLUX = 0.0
      RETURN
C
  10  CONTINUE
      FLUX = 0.0
      DO 20 I=1,NQ
      J = I
      TD = T(I)
      IF( TREL.LE.TD ) GO TO 30
  20  CONTINUE
C
      WRITE(6,35) KSTEP,KINC,TIME,NOEL
  35  FORMAT(/,'  WARNING - PASSED THROUGH DFLUX WITHOUT ASSIGNING',
     &      /,'          FLUX.  STEP =',I5,'  INC =',I5,
     &      /,'          TIME =',F12.2,'  ELEMENT =',I5)
      RETURN
```

"Flux value is converted from units of hours to units of days."

```
  30  FLUX=Q(J)*24.0
C     WRITE(6,99) FLUX,TIME,TEMP,KSTEP,KINC,NOEL,NPT
```

```
C 99  FORMAT(3G15.6,4I8)
      RETURN
      END
```

*** USER SUBROUTINE HETVAL ***

```
      SUBROUTINE HETVAL (CMNAME,TEMP,TIME,DTIME,SVAR,FLUX,PREDEF)
      IMPLICIT REAL (A-H,O-Z)
      DIMENSION SVAR(1),PREDEF(1)
      CHARACTER*8 CMNAME
C*******************************************************************
C
C     Calculate and return Volumetric Heating Rate at each integration
C     point for each concrete element by material name  R James 10/27/92
C     This method is independent of element numbers - Each lift is
C     given a material name using *HEAT GENERATION material option
C
C     NQ1  is no. of points in T1 & Q1 arrays
C     Start time for each lift based on 5 day placement increments
C     NOTE - FLUXES IN Q1 ARRAY OBTAINED FROM WES
C         - ASSUMED UNITS ARE BTU/(hr-in**3)
C         - BASED ON SPEC. WT = 0.08449,  SPEC.HEAT = .22 & HOURS
C
C*******************************************************************
C
      PARAMETER (NQ1=21)
      DIMENSION Q1(NQ1),T1(NQ1)
      SAVE Q1,T1
C
"T1 contains the time (in hours) associated with each value of
 flux given in Q1."
      DATA T1 /    6.00,   12.00,   18.00,   24.00,   30.00,
     $            36.00,   48.00,   60.00,   84.00,  108.00,
     $           120.00,  144.00,  168.00,  192.00,  216.00,
     $           240.00,  264.00,  288.00,  336.00,  360.00,
     $           648.00 /
      DATA Q1 /0.00846090,0.01001042,0.01284686,0.00521171,0.00539755,
     $         0.00567338,0.00520116,0.00414147,0.00338928,0.00279045,
     $         0.00224723,0.00194696,0.00160559,0.00138042,0.00117012,
     $         0.00091299,0.00071519,0.00058468,0.00037927,0.00030453,
     $         0.00015165 /
C
      FLUX = 0.0
C
C       Find lift number of current material
C     Assume name is of form xxLIFTii where ii is lift number
C
      L = INDEX(CMNAME,'LIFT')
      IF (L .EQ. 0) RETURN
      READ (CMNAME(L+4:L+5),100) LIFT
```

```
  100 FORMAT (I2)
      IF (LIFT .EQ. 0) RETURN
C
C   Compute start time of lift based on 5 day placement intervals
C
      START = FLOAT(LIFT-1) * 5.0
      TREL = (TIME - START) * 24.
      IF (TREL .LT. 0.0) RETURN
```

"TREL is the relative time of each lift in the analysis. START and TREL assume that concrete is placed at day 0 of the analysis."

```
C
C   Find discrete flux value - no interpolation
C
      DO 20 I=1,NQ1
      IF (TREL .LE. T1(I)) THEN
```

"Convert fluxes to units of days"

```
        FLUX = Q1(I) * 24.
        GOTO 40
        ENDIF
   20 CONTINUE

C
C   Heat generation is zero if relative time is past T1(NQ1)
C
   40 CONTINUE
CC      PRINT 9000, CMNAME,LIFT,TIME,TREL,FLUX
CC 9000 FORMAT (' MATERIAL,LIFT,TIME,TREL,FLUX = ',A8,I4,3(1X,1PG12.4))
      RETURN
      END
```

ANNEX 4: PARAMETERS REQUIRED FOR NISA INPUT

A4-1. List of Parameters

The items listed are the various parameters required for input when performing a NISA. More information on each of these parameters can be found in the main text. Parameters which are based on test results will be designated with an *.

a. Heat transfer analysis.

(1) Extreme ambient air temperature.

(2) Film coefficients (for convection).

- without formwork
- with formwork
- with insulation
- at various wind speeds

(3) Initial distribution of temperature in foundation.

(4) Boundary temperature condition at base of foundation.

(5) Placing temperature of the concrete.

(6) Relative analysis time when each lift is placed (based on sequence and intervals of lift placements).

(7) Conductivity.

- concrete *
- foundation
- air

(8) Specific heat.

- concrete *
- foundation
- air

(9) Density.

- concrete *
- foundation
- air

(10) Adiabatic temperature rise curve * (to be used in DFLUX or HETVAL).

b. Stress analysis.

(1) 3-day modulus of elasticity *.

(2) 3-day compressive strength *.

(3) Fracture strain * (computed from slow load test data as described in Annex 2, this appendix).

(4) Modulus of elasticity curve (aging modulus) * (to be used in ANACAP-U).

(5) Creep curve * (to be used in ANACAP-U).

(6) Shrinkage curve * (to be used in ANACAP-U).

(7) Coefficient of thermal expansion*.

(8) Type of concrete model used in ANACAP-U (WES model is model 4).

(9) Poisson's Ratio *.

(10) Time of set (age at which concrete can begin to carry load) *.

(11) Creep factor (bandwidth percentage).

(12) Shrinkage factor (bandwidth percentage).

(13) Number of concrete mixtures used in the analysis.

(14) Boundary conditions.

- symmetry
- lateral restraint for foundation

(15) Foundation, piles.

- lateral spring coefficient
- vertical spring coefficient (piles & soil)

(16) Foundation, soil.

- vertical spring coefficient

or

- density
- modulus of elasticity
- Poisson's Ratio

(17) Foundation rock.

- density
- modulus of elasticity
- Poisson's Ratio

or

- lateral spring coefficient
- vertical spring coefficient

(18) Temperatures from the heat transfer analysis.

(19) Equivalent gravity loads.

(20) Service loads.

ANNEX 5: NISA TECHNICAL REPORT

A5-1. General

The required DM discussed in paragraph 7 of the main text is not intended to cover all of the details associated with performing and evaluating a NISA. Therefore, in addition to the DM which must be submitted to higher authority, a technical report outlining all of the details of a NISA should be developed as an appendix to the DM. This report should include the details on the development of the various parameters selected for performing the analysis and a detailed presentation of the results of the analyses from which the evaluation of the structure was made. Since the DM will be developed primarily from this technical report, the items described in the DM will be repeated in this annex. The items which should be included in the report are presented.

A5-2. Report Requirements

a. Introduction. The report shall have an introduction which provides general information about the project and any pertinent developments which occurred leading up to performance of the NISA. The introduction should also include the objectives of the NISA study as well as the scope of the work to be performed.

b. Material parameters. This section should include a brief presentation of the concrete and foundation materials to be used at the project and a description of how these materials will be used in the NISA. This should include a brief description of the results of the calibration of the material model used in the UMAT subroutine.

c. Modeling parameters. There should be a detailed discussion of the modeling parameters used in the analyses. As a minimum requirement there shall be discussion on the following items:

(1) Finite element mesh selection.

(2) Film coefficients.

(3) Parametric combinations used.

(4) Boundary conditions.

(5) Process for selecting the ambient temperature curve.

(6) Initial conditions.

d. Presentation of results. Minimum requirements for presentation of results are listed. Presentation of results is critical in providing the proper understanding of how the structure behaved and for supporting any conclusions or recommendations that will be made as a result of the NISA.

(1) Results from initial parametric studies which were used as the basis for design decisions or subsequent analyses.

(2) Temperature contour plots at times when temperatures are at the maximum and when large gradients across structural members exist.

(3) Temperature time histories of points where stress time histories are presented.

(4) Stress contour plots at times of maximum stress.

(5) Stress time-history plots at points of maximum stress and at critical points in the structure.

(6) Stress distributions across members which may be considered critical and across members where maximum stress values are occurring. The distributions of stress should be compared to stress distributions obtained from a conventional linear, elastic finite element analysis.

(7) Contour plots of the crack potential for points in the time history where the maximum percentages of cracking occur.

(8) If cracking occurs, plots of the cracking which has occurred.

e. Conclusions and recommendations. Based on the parameters selected and any assumptions made when selecting these parameters along with the results presented, conclusions and recommendations resulting from the NISA study should be presented. The conclusions and recommendations should also be presented in light of the objectives which were stated in the introduction to the report.

APPENDIX B: EXAMPLES

B-1. General

The information in this appendix is provided to assist the designer in understanding certain aspects of performing a nonlinear, incremental structural analysis (NISA). Included are discussions on mesh size and selection, evaluation of cracks and crack potentials, and a parametric study of varying the placing temperature of the concrete. The information presented in this enclosure was taken from the report on the Olmsted project "Nonlinear, Incremental Structural Analysis of Olmsted Locks and Dam, Volume I" ((Garner et al. 1992) listed in Reference section of Appendix A).

B-2. Mesh Size and Selection

a. General. As described in paragraph 5*c*, Appendix A, there are certain restrictions on element size which must be maintained when developing a mesh for a NISA. Considerations must be given for certain restrictions in the heat transfer analysis as well as ensuring that enough elements are present in the model to capture the structural response in the stress analysis, which includes using two rows of elements per lift of concrete and at least two elements through the thickness of any given member. While it is important to adhere to the requirements listed in Appendix A, in some instances it may become necessary to exceed the criteria with respect to the number of elements and the size of elements to reduce computing time and the amount of output data. The following discussion provides insight into the mesh development for the NISA which was performed on the typical chamber monolith of the Olmsted Locks.

b. Olmsted chamber monolith. Figure B-1 is a sectional elevation of a typical chamber monolith of the Olmsted Locks and the finite element (FE) mesh used in the NISA study of the monolith. The Olmsted project implemented the innovative concept of a W-frame lock which has a common wall between the two lock chambers and is a variation on the more common U-frame type lock. The dimensions of the monolith are typical for a massive reinforced concrete structure.

(1) Heat transfer analysis considerations. Due to the algorithm used in ABAQUS for performing the heat transfer analysis, a criterion for the element size is given in paragraph 5*c*(5), Appendix A. Based on this equation, a minimum timestep of one-quarter day and the other necessary data from the Olmsted project, the maximum element size which may be used in the heat transfer analysis is 26.9 in. As can be seen in Figure B-1, the majority of the mesh adheres to the criterion given in paragraph 5*c*(5), Appendix A. It is only toward the center of the slab that the criteria is exceeded and it is exceeded only in the horizontal direction. Truman, Petruska, and Ferhi (1992) (listed in Reference section of Appendix A) show that it is acceptable to exceed the criteria in the direction perpendicular to heat flow. Since the direction of heat flow in the slab, away from the walls, is vertical, then it is acceptable to increase the element size above the criterion in the horizontal direction.

(2) Stress analysis considerations. As stated in paragraph 5*c*, Appendix A, conventional FE modeling techniques should be adhered to when developing a mesh for a NISA. In addition, paragraph 5*c*(2) discusses some specific areas where these techniques can be supplemented. As can be seen in Figure B-1, the mesh for the Olmsted chamber monolith follows these suggested guidelines. There are at least two elements in every lift and at least two elements through the thickness of every member.

c. Additional considerations. While the chamber monolith from the Olmsted project followed the guidelines for mesh size and selection as outlined in Appendix A, following these guidelines may not always be practical, particularly in three-dimensional analyses. Any deviation from the criteria and guidelines outlined in paragraph 5*c*, Appendix A, should be evaluated on a case-by-case basis. Parametric studies may be appropriate to justify exceeding the restrictions in some cases, where in other cases past experience and engineering judgement can be used.

B-3. Evaluation of Cracks and Cracking Potentials

a. General. Due to the low tensile capacity of concrete, cracking is likely to occur in any concrete structure. While cracking can be expected on massive concrete structures, it is the size and location of

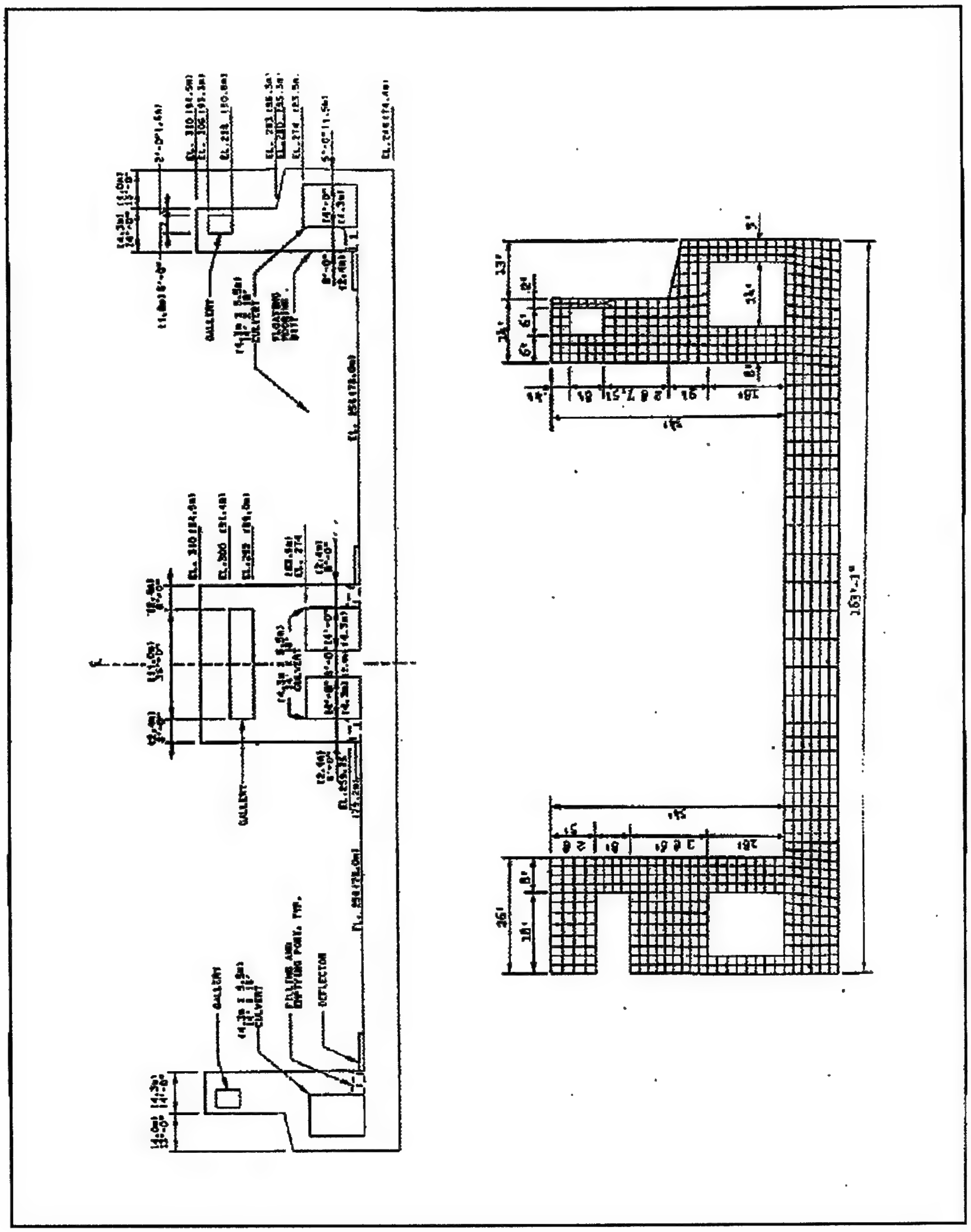

Figure B-1. Sectional elevation of a typical chamber monolith at Olmsted Locks and the NISA finite element mesh

the cracks that form which are important as well as areas where there is a high potential for cracking. If a NISA shows that only a few integration points exceed the cracking criteria (discussed in Annex 2, Appendix A) and the analysis shows that the cracking has stopped, then measures to reduce the cracking may not be necessary, particularly if reinforcing is present. If it is shown though that the cracking extends through the depth of a member, then consideration must be given to making changes to reduce the cracking regardless of the fact that reinforcing is present. This section will discuss cracking potentials and crack plots and how to use this information. The chamber monolith shown in Figure B-1 is used for this presentation. It should be noted that the cracking criteria was reduced by one-half in the following analyses so that cracking would occur.

b. Crack plots.

(1) Figures B-2 through B-5 are crack plots of the middle wall and one-half of the chamber and Figures B-6 and B-7 are crack plots of the land wall and one-half of the chamber. As can be seen in Figure B-2, no cracks have formed at 81.5 days (time of the analysis is designated by the AMP parameter located at the top of the plot). Figure B-3 is a plot at 85.75 days and as can be seen, an integration point above the top left corner of the culvert has cracked. It can be seen by looking at Figures B-4 and B-5 that the crack does not extend beyond this initial cracking. Such a crack would typically not require taking measures to eliminate the crack, particularly for a reinforced structure.

(2) Figure B-4 is a plot at 143 days and an integration point has cracked at the lower left hand corner of the culvert and six integration points have cracked approximately one-third of the way across the slab. As can be seen in Figure B-5, 20 days after the condition shown in Figure B-4, the crack at the bottom corner of the culvert has not grown, but the crack in the slab has extended further into the slab. The crack as shown in Figure B-5 is as far as the crack advanced. As with the crack at the top of the culvert, no additional steps should be needed at the bottom of the culvert. The crack in the slab may need to be evaluated further. The design team should evaluate a crack such as the one seen in Figure B-5. Then, based on the load causing the crack and the stresses in the reinforcing, a decision should be made as to whether steps should be taken to reduce or eliminate the crack. Since the crack seen in the slab in Figure B-5 was created due to ambient conditions and the stresses in the reinforcing are low, it would be reasonable to allow the construction parameters to remain unchanged.

(3) Figure B-6 shows the cracking which has begun to occur on the land wall half of the slab. Three integration points have cracked initially and do not extend beyond the top lift. Figure B-7 shows the final crack pattern in this portion of the slab at day 183 and only one additional integration point has cracked. As with the cracking which occurred in the other portion of the slab, the crack indicated by the plots does not continue to propagate. If stresses in the reinforcing are evaluated, they are low, so as before, changes in the construction parameters to reduce or eliminate the cracking shown do not appear to be necessary.

c. Crack potential plots.

(1) Figures B-8 through B-14 are crack potential contour plots of the middle wall half of the model, while Figures B-15 through B-18 are crack potential contour plots of the land wall half of the model. The contours shown in these plots provide information about how close to cracking various parts of the structure are in the form of percentages of the cracking criteria, i.e., a 50 percent contour indicates that the level of stress and strain is one-half the cracking criteria. These plots can be used to identify areas that are near the cracking level.

(2) Figure B-8 is a crack potential plot of the left half of the model at day 81.5 which is just a few days prior to the crack occurring at the top left corner of the culvert. As can be seen in the figure, high cracking potentials are developing at this corner. An enlarged view of the culvert is shown in Figure B-9 and in this figure it can be seen that the potential for cracking at the corner in question is approximately 70 percent. Figure B-10 is the enlarged view of the culvert again, but it is shown at day 85.75, which is the step after the crack has formed at the corner. As can be seen, the cracking potential near the corner has been reduced, and the potential for cracking of 66 percent is occurring more toward the center of the culvert.

(3) Figure B-11 again shows the left half of the model at day 103. The potential for cracking near the top left corner of the culvert continues to build to a level of 88 percent. In addition, the top of the slab

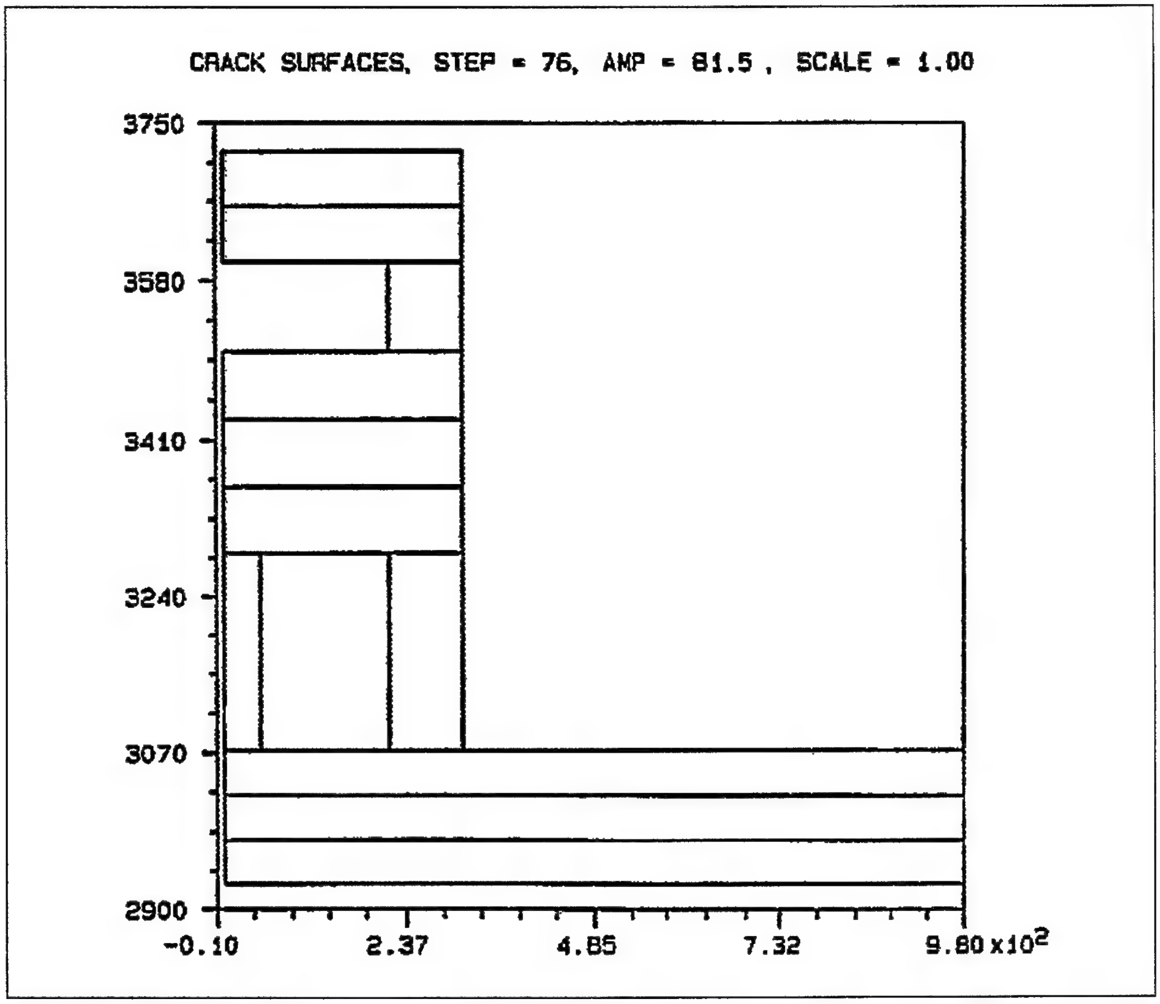

Figure B-2. Crack plot at day 81.5 of the middle wall half of the chamber monolith model

has portions which are over 50 percent. Figure B-12 shows contours at day 115 and the potential at the top of the slab has risen to over 70 percent, but the crack potential at the top of the culvert has begun to decrease. In addition, note that a potential of 89 percent exists at the top of the lift above the gallery. This high potential and the crack potential building in the slab are due to ambient condition which is entering the winter season. Figure B-13 is taken at 143 days and is after the cracking in the slab has initiated. The cracked area has reduced potentials near the top of the slab, but a potential of 96 percent remains at the bottom of the top lift. Note to the right of the cracked area, the cracking potential is nearly parallel with the top surface indicating a uniform level of cracking potential across the top of the slab. Figure B-14 is the cracking potential after all of the cracking has occurred in this portion of the slab. Note that the potentials in the area of the crack are lower than in other areas, but they have not all gone to zero. This is because tensile stresses and strains which may still be present but are not perpendicular to the crack surface continue to be evaluated against the cracking criteria.

(4) Behavior of the right half of the model is similar to the left half as seen in Figure B-15. An area of high potential is building in the top of the slab (68 percent) and also at the corner of the culvert, although the potentials at the culvert corner are much lower than those observed on the left half of the model. Both of these potentials continue to build,

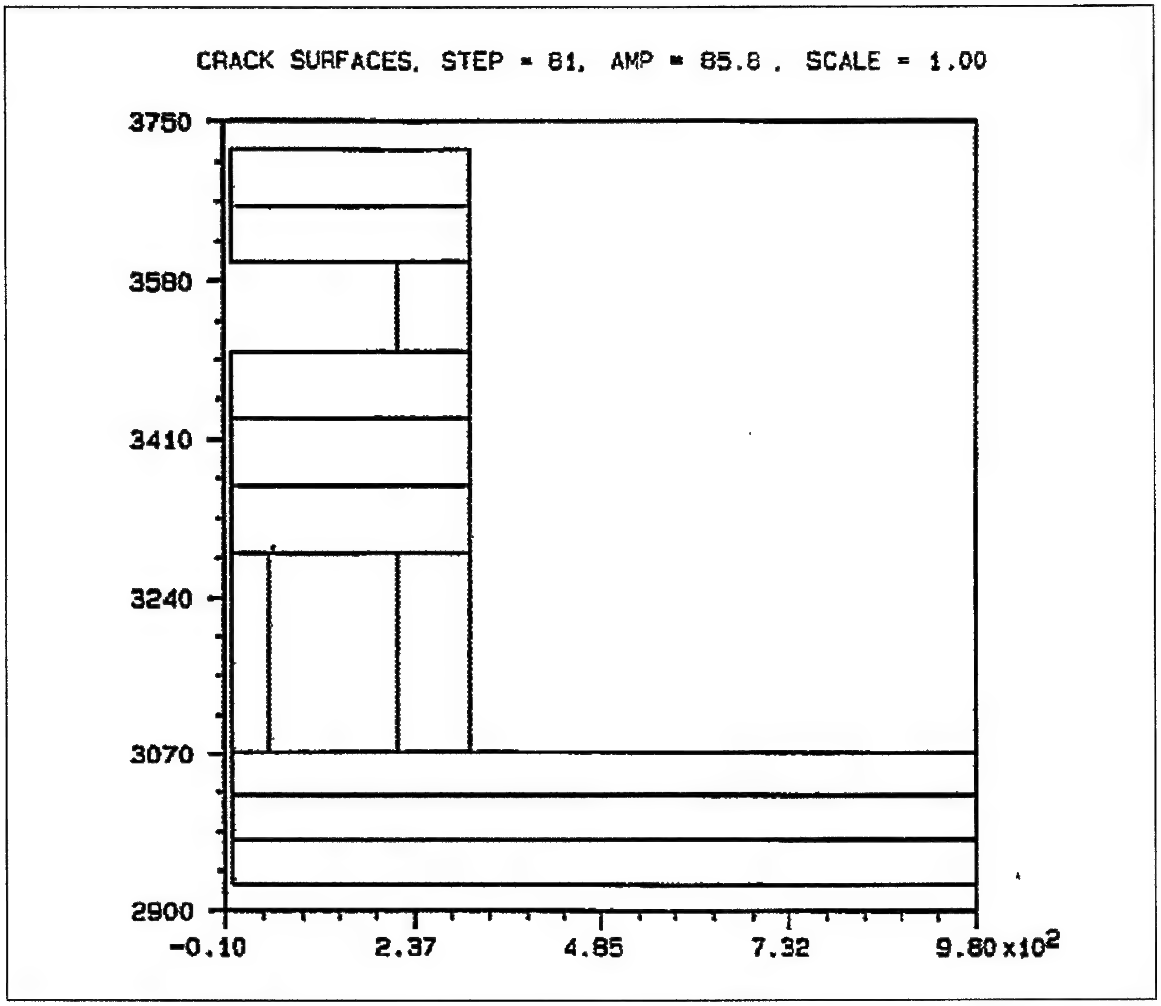

Figure B-3. Crack plot at day 85.75 of the middle wall half of the chamber monolith model

particularly in the slab as seen in Figure B-16 (day 143) where a potential of 96 percent occurs. Figure B-17 is a plot at day 163 after the initial cracking in this portion of the slab has occurred. The location of the crack is obvious from the reduced area of potential. Also, the point where the next integration point will crack can be seen in the figure by the designation of the 98 percent cracking potential. The potentials after all of the cracking has occurred are shown in Figure B-18 and are similar to what was observed in the left half of the model.

B-4. Placing Temperature Parametric Study

a. General. One of the parametric studies performed during the course of the Olmsted project's NISA study was an evaluation of concrete placing temperatures. It is a regular practice in mass concrete construction to reduce the temperature of the concrete when it is placed as a means of reducing the maximum temperature that the concrete will reach since lowering the maximum temperature can reduce thermal stresses in the concrete. The initial assumption

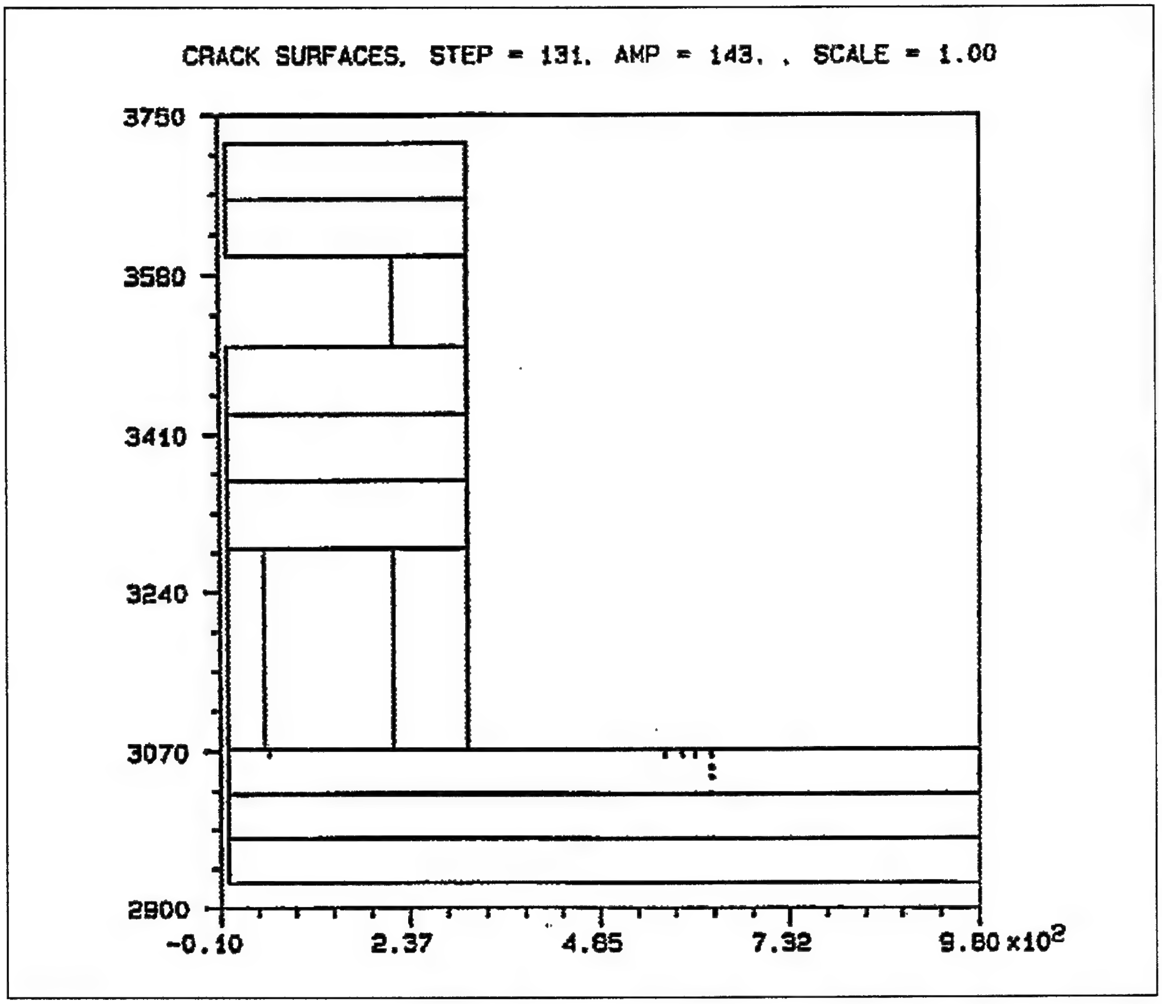

Figure B-4. Crack plot at day 143 of the middle wall half of the chamber monolith model

for the concrete placing temperature for lock construction was 60 °F. Since cooling the concrete to this temperature during the summer months would require adding ice in place of water or including liquid nitrogen to the mixture, it was determined that higher placing temperatures should be evaluated to determine if costs associated with cooling the concrete could be reduced. Two additional analyses were performed. One analysis used a placing temperature of 70 °F, and the other used a placing temperature equivalent to the ambient temperature at the time the lift was placed. The study was performed on the chamber monolith of the Olmsted project as shown in Figure B-1.

b. Analysis results.

(1) Temperature results. The results of the heat transfer analysis should first be evaluated for the three cases under consideration. Time-history temperature plots are presented for three points in the slab in Figures B-19 through B-21. The initial observation on all three plots is that a noticeable difference exists when the concrete is first placed due to the different placing temperatures for each case, but at 300 days very little difference exists between the three analyses. It should also be noted that while the general shape of the curves in all three figures follow the shape of the ambient temperature curve

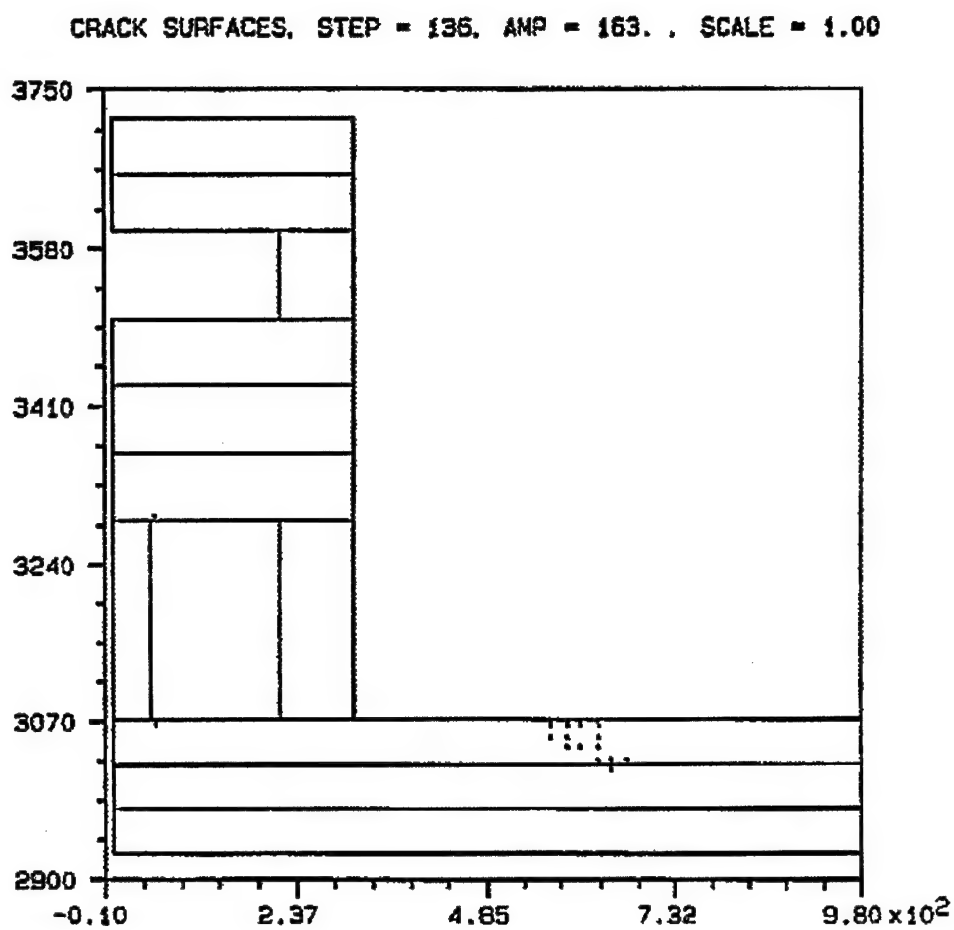

Figure B-5. Crack plot at day 163 of the middle wall half of the chamber monolith model

(designated in the plots by "Extreme Ambient"), node 3371 near the top of the slab follows the ambient much more closely than the other two curves. If the plots from the three figures were superimposed upon one another, a substantial temperature gradient would occur from the top to the bottom of the slab at approximately day 200.

(2) Stress results. Plots of stress used in evaluating the results are shown Figures B-22 through B-26. Figure B-22 is a time-history plot of the horizontal stress at the point of maximum stress in the chamber monolith. As mentioned previously, in the past it has been assumed that a higher placing temperature would create the worse condition, but Figure B-22 shows that this is not the case in this instance. The maximum stress for the 60 °F placing temperature case is approximately 80 psi higher than the maximum stress at this point for the ambient placing temperature case. While these results do not match conventional understanding from analysis of mass concrete structures, there is a logical explanation. The results shown in Figure B-22 are essentially a surface effect as shown in the stress distribution plot in Figure B-23. Surface effects cause the stress to be lower for the ambient placing temperature, but at other points through the slab thickness this is not necessarily the case. A time history at the second

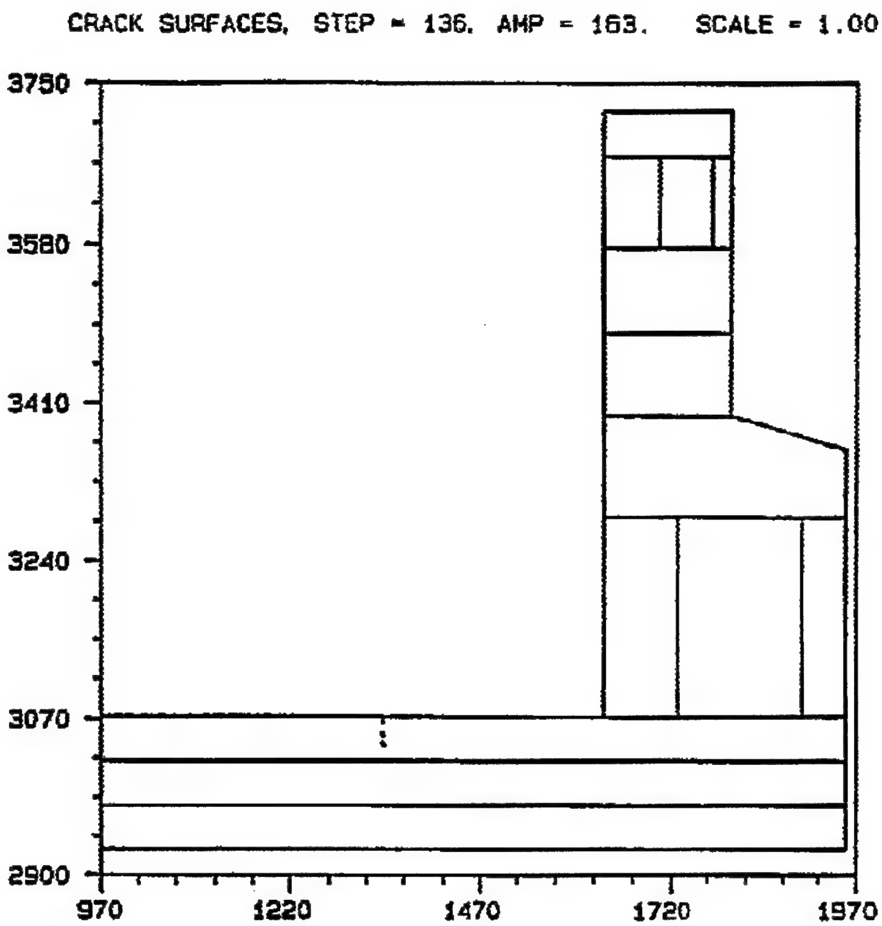

Figure B-6. Crack plot at day 163 of the middle wall half of the chamber monolith model

point from the surface (Figure B-24) shows how the ambient placing scheme has become the more critical of the three cases.

(a) The reason for the behavior exhibited at the top integration point of the slab can be explained if the beginning of the time history is looked at more closely as shown in Figure B-25. As can be seen, the initial stress history of the three cases shows that the ambient placement case produces tensile stresses almost immediately while the other two cases go into compression first. It is at these early times that the highest rate of creep is occurring. Therefore, tension at early times is being relieved for the ambient placement case, while compression is being relieved for the other cases. Since this is a time-history analysis and the stiffness matrix is reformulated with each step based on strain state of the previous step, the relief of stresses occurring has an impact on the results at later times in the analyses, hence the lower stresses for the ambient placement case at day 200.

(b) Finally, Figure B-26 shows a time history of the maximum principal stress at a point in the wall. For this point the ambient placement case controls, but the stresses are relatively low and therefore are not a major concern.

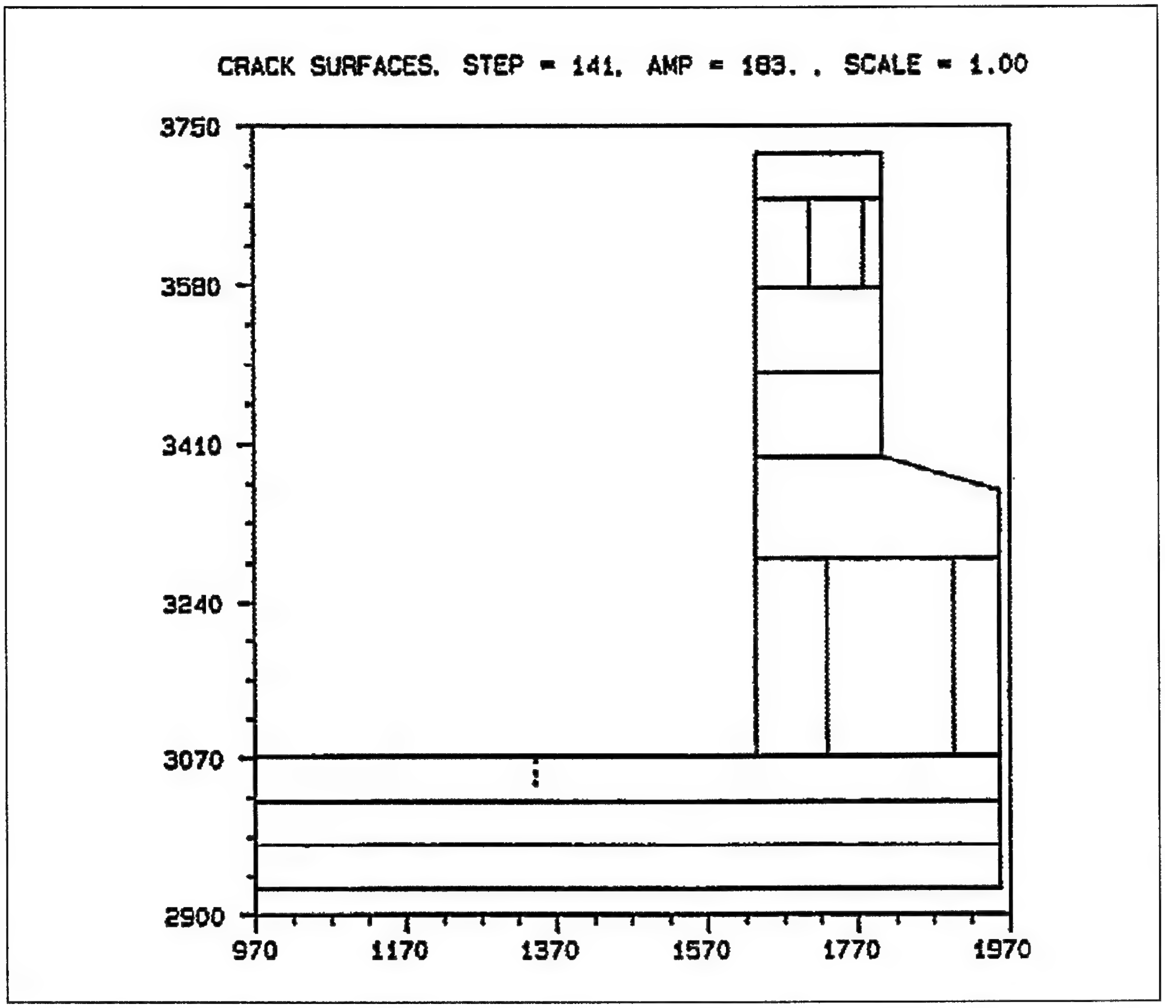

Figure B-7. Crack plot at day 183 of the land wall half of the chamber monolith model

c. Conclusion. Based on the results of the analyses, a conclusion could be drawn that the ambient placement condition was acceptable and could be used during construction for these types of monoliths. Based on the results of the analyses combined with experience of engineers from Headquarters, U.S. Army Corps of Engineers; U.S. Army Engineer Division, Ohio River; U.S. Army Engineer District, Louisville; and the U.S. Army Engineer Waterways Experiment Station, a decision was made to specify a maximum placing temperature of 75 °F.

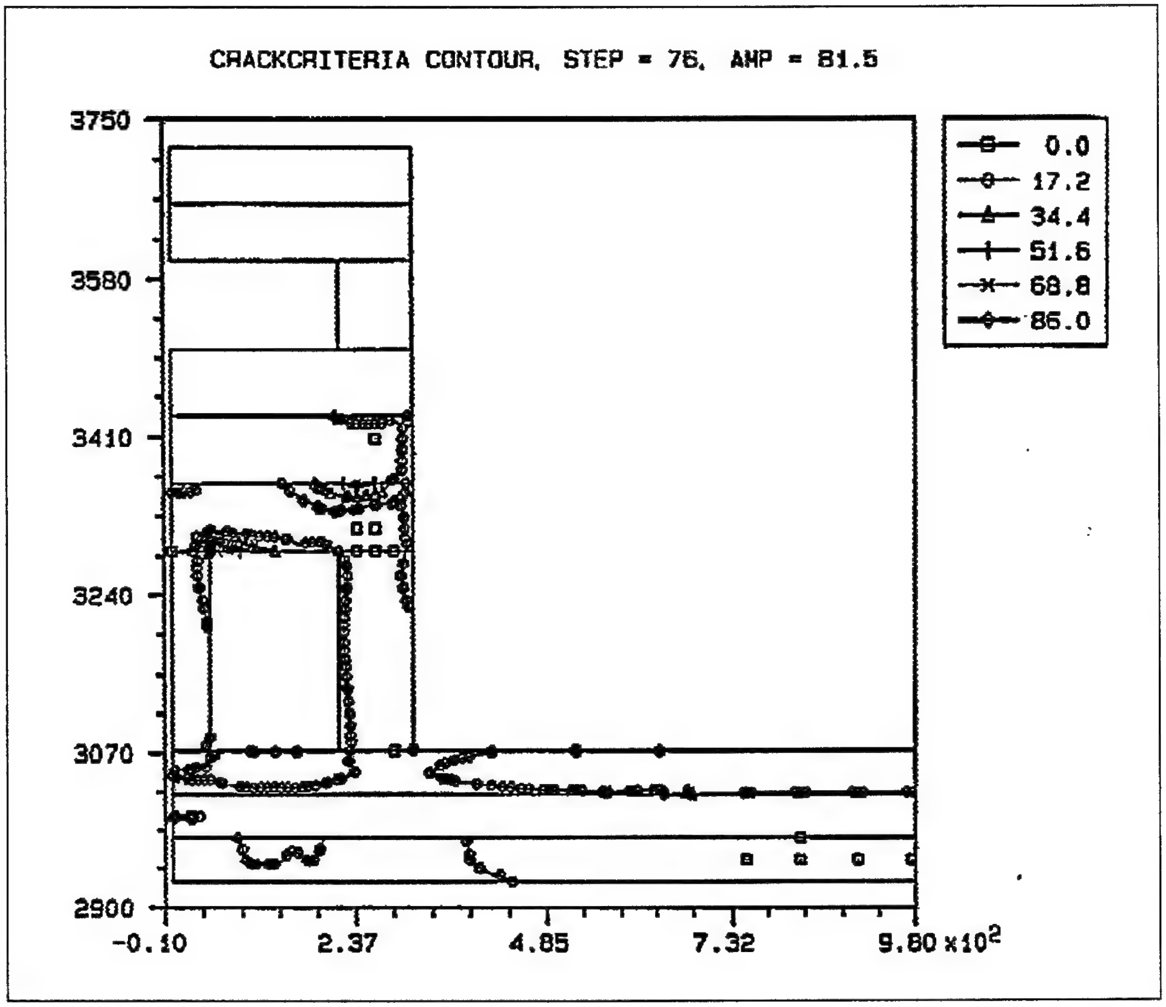

Figure B-8. Crack potentials at day 81.5 of the middle wall half of the chamber monolith model

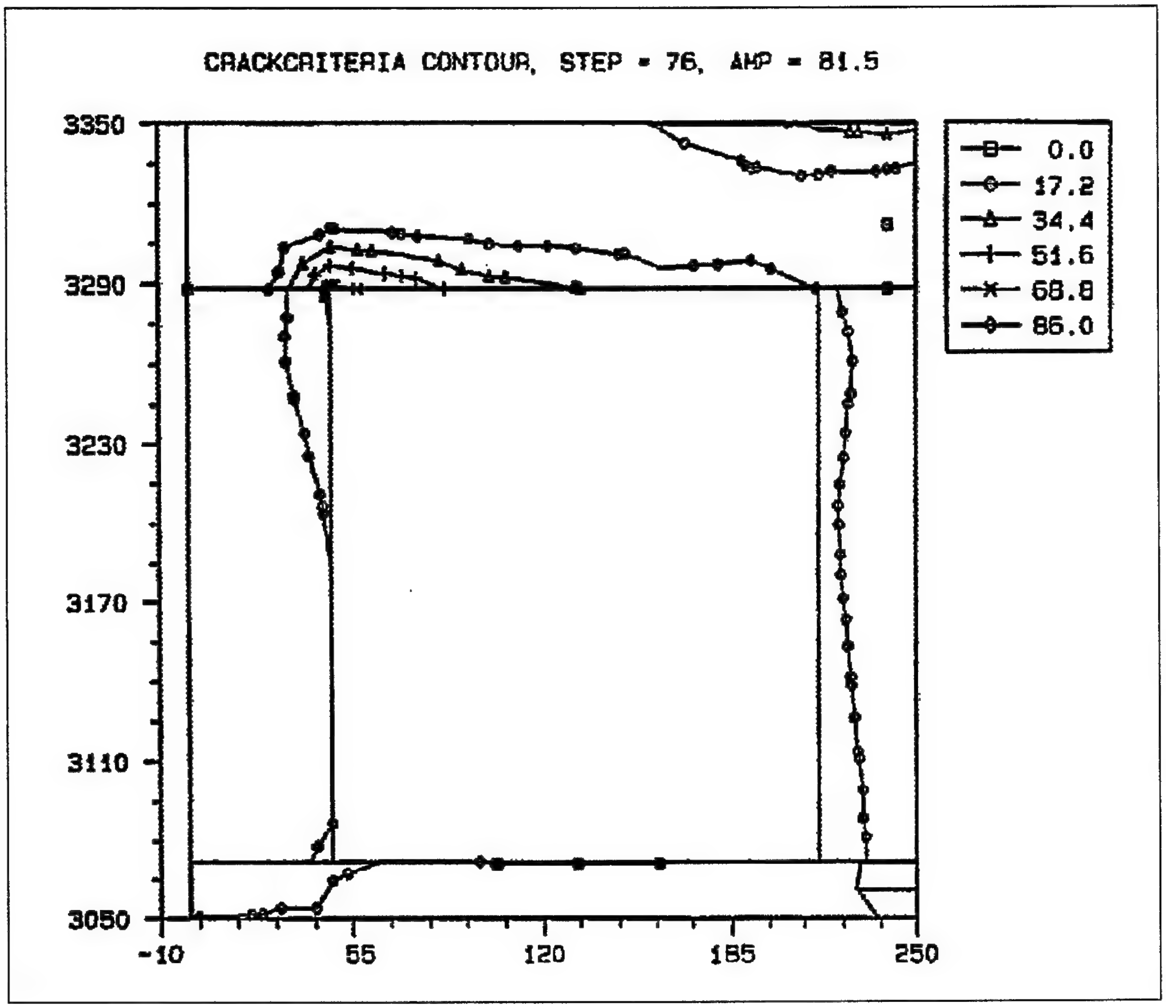

Figure B-9. Enlarged view of crack potentials from Figure B-8 around the culvert at day 81.5

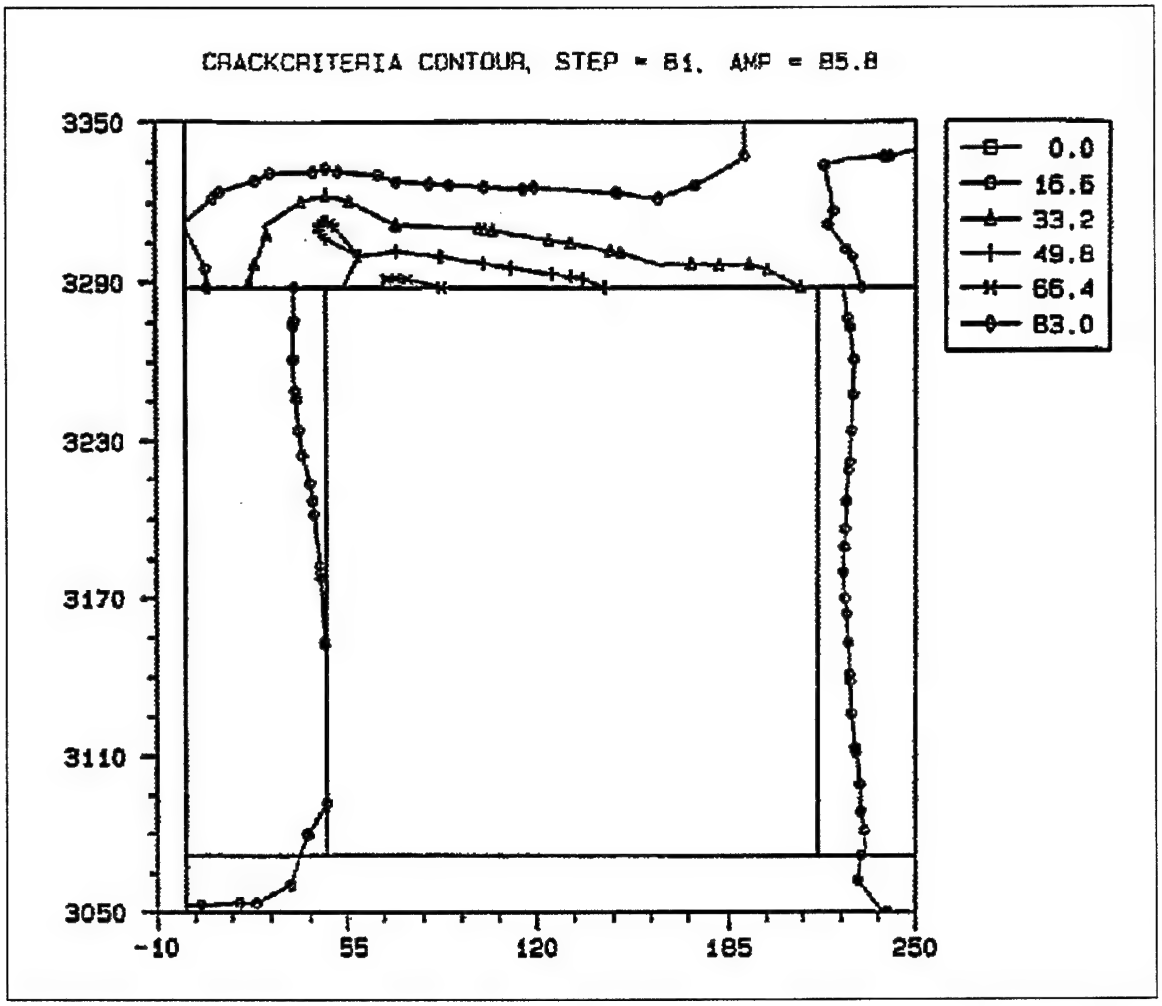

Figure B-10. Enlarged view of crack potentials from Figure B-8 around the culvert at day 85.75

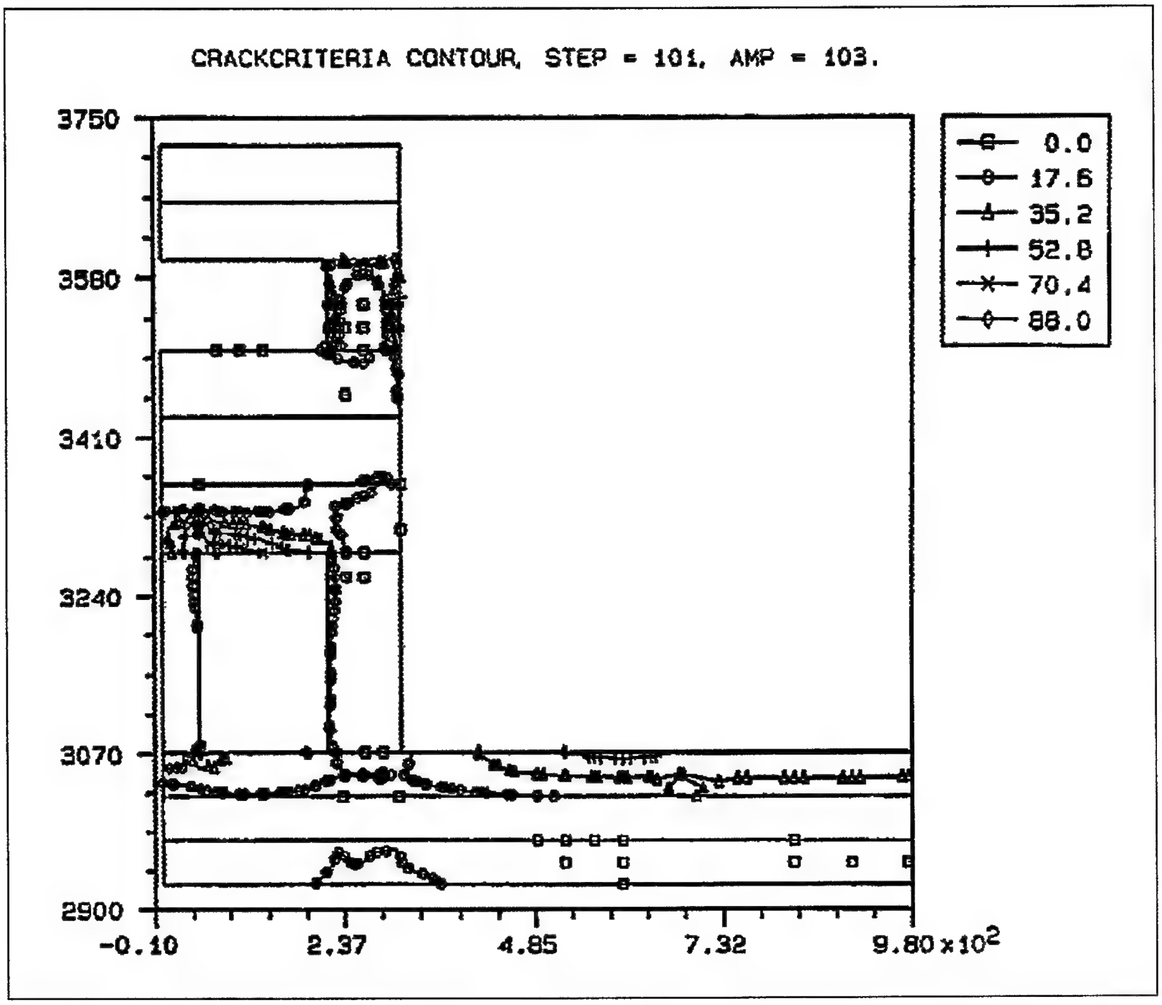

Figure B-11. Crack potentials at day 103 of the middle wall half of the chamber monolith model

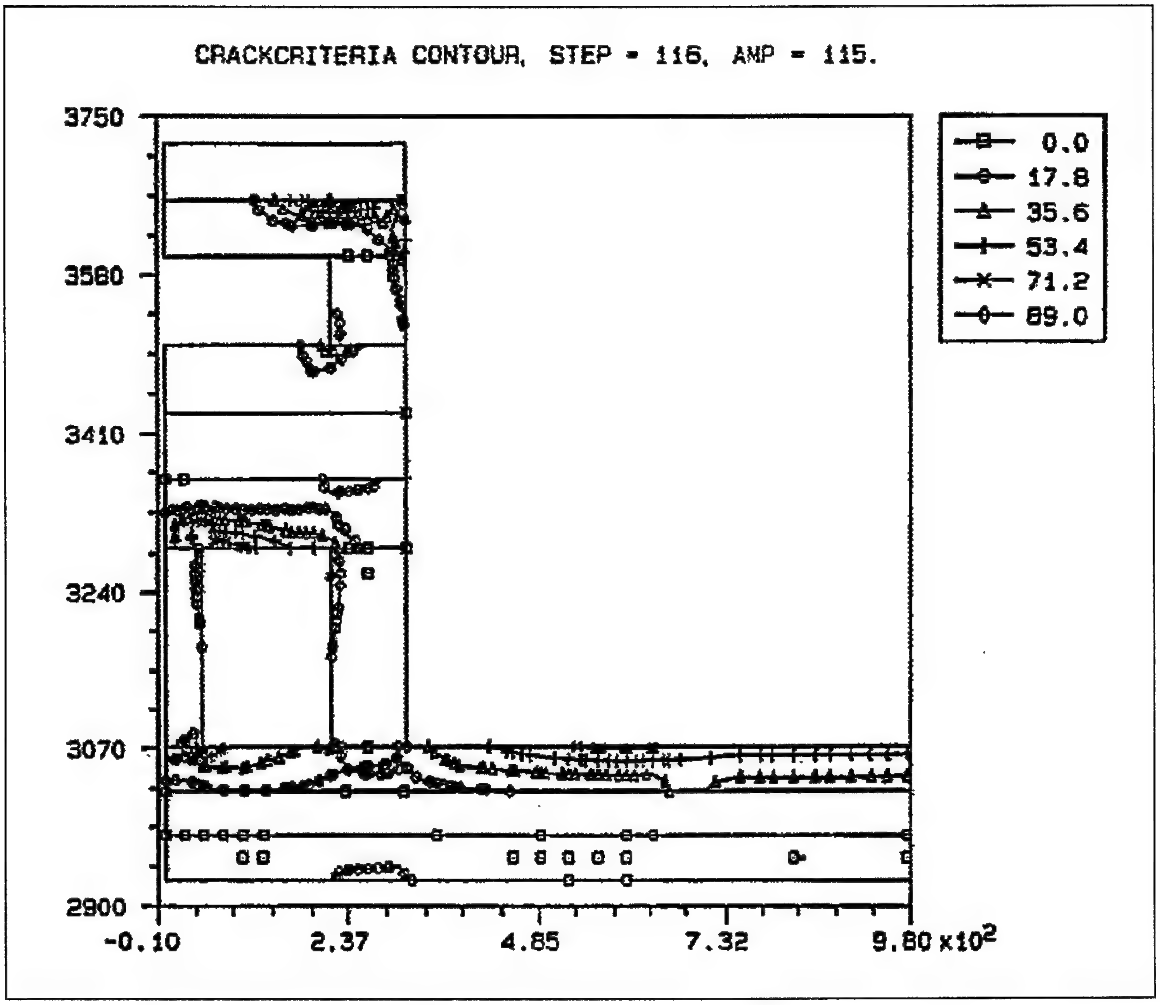

Figure B-12. Crack potentials at day 115 of the middle wall half of the chamber monolith model

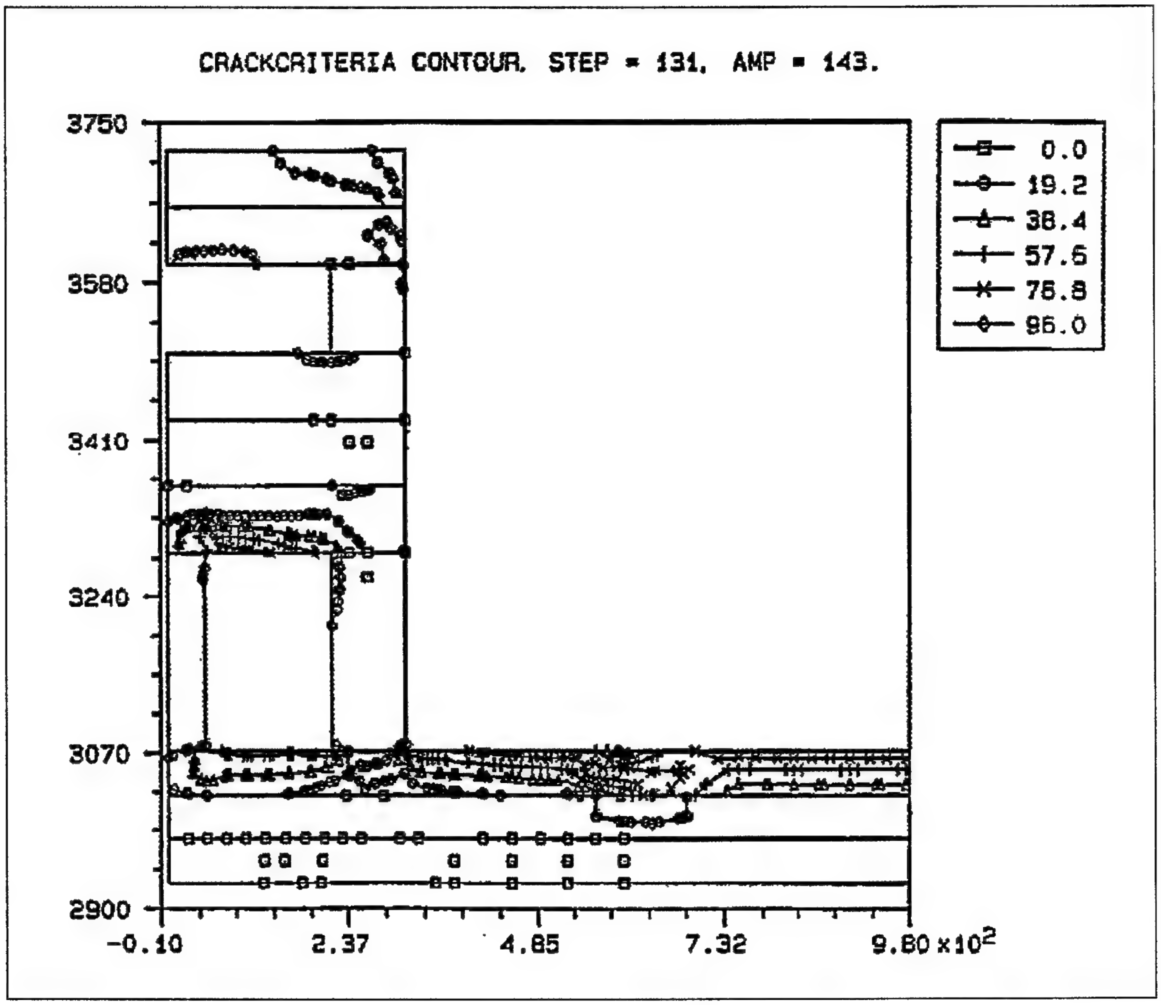

Figure B-13. Crack potentials at day 143 of the middle wall half of the chamber monolith model

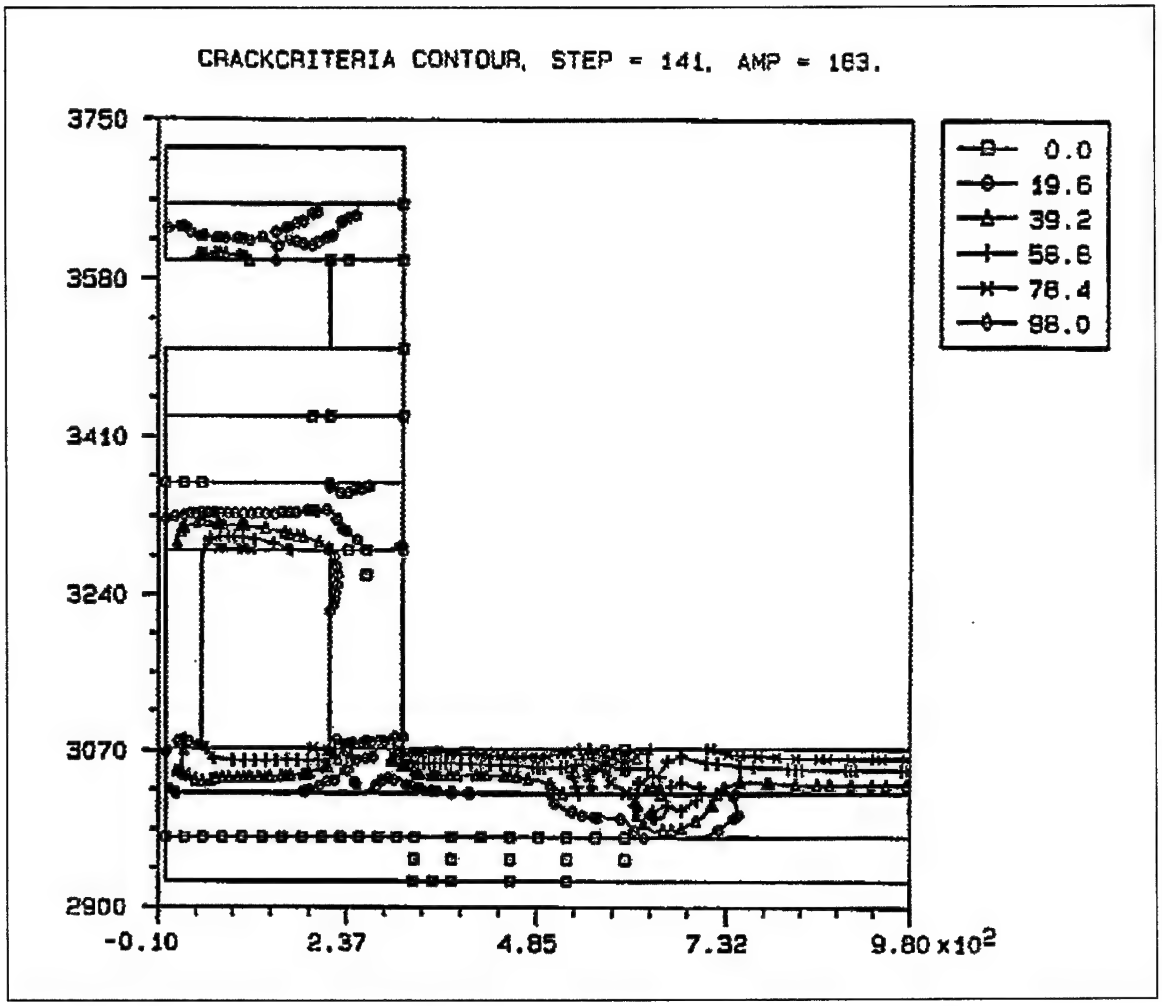

Figure B-14. Crack potentials at day 183 of the middle wall half of the chamber monolith model

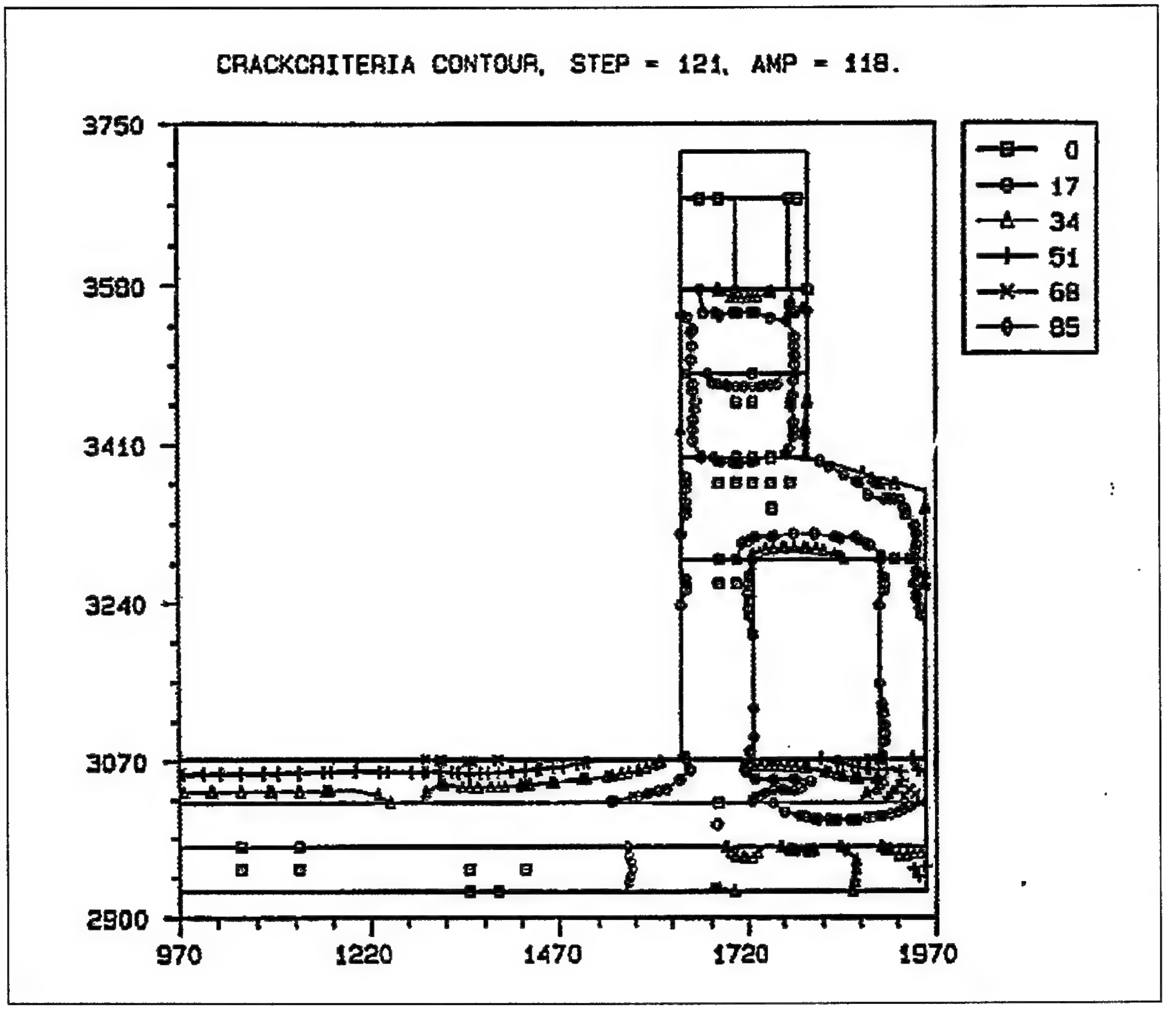

Figure B-15. Crack potentials at day 118 of the land wall half of the chamber monolith model

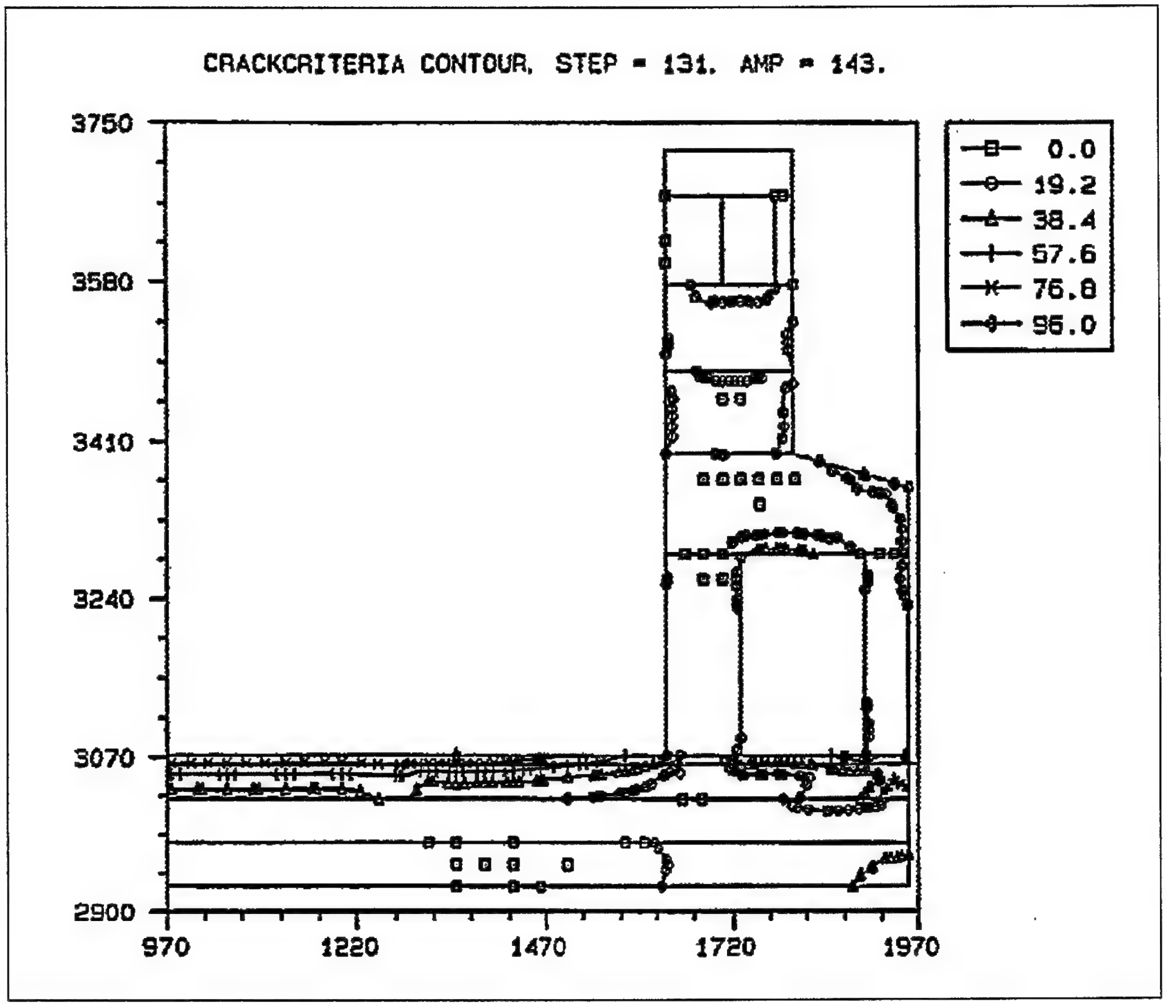

Figure B-16. Crack potentials at day 143 of the land wall half of the chamber monolith model

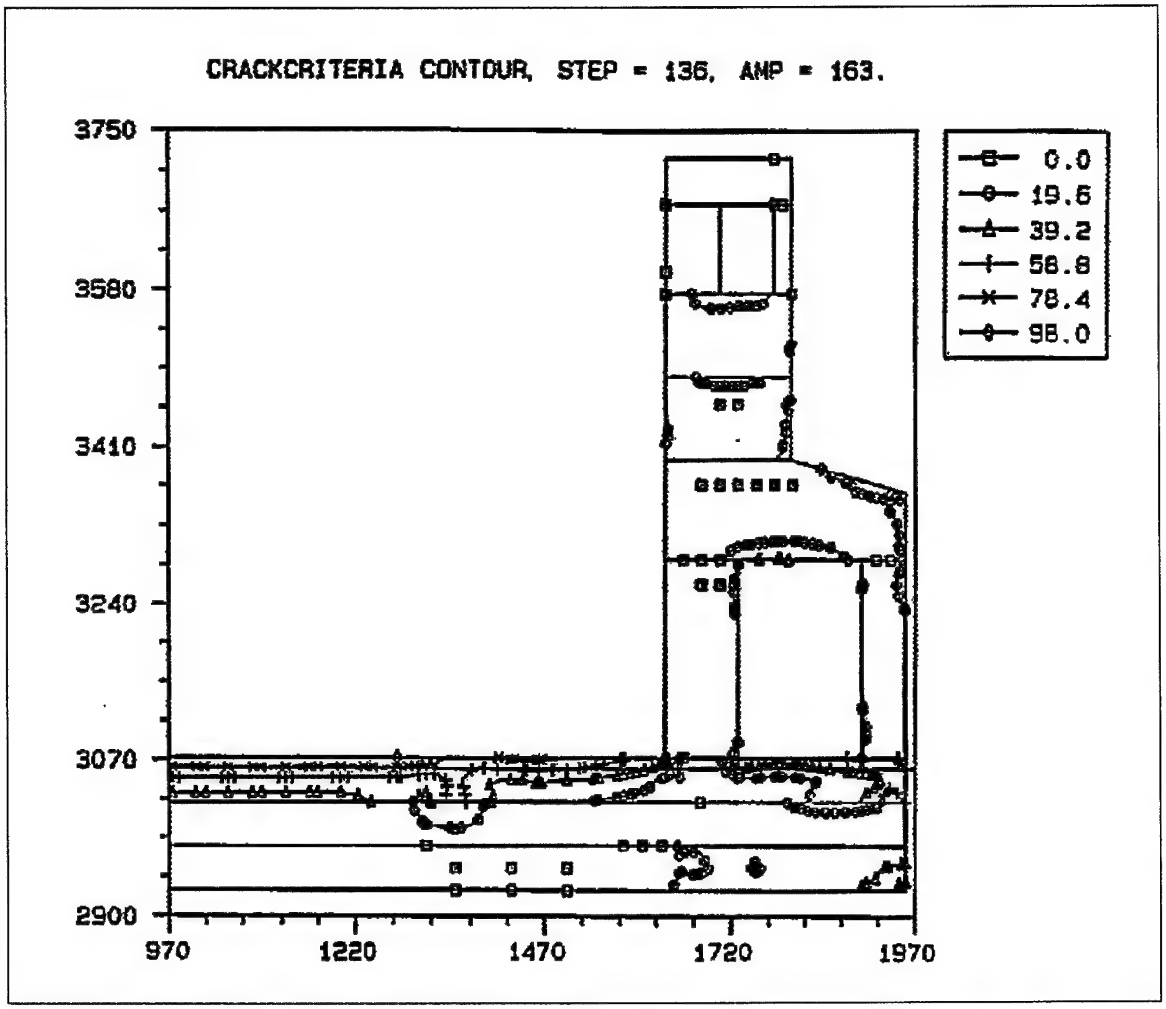

Figure B-17. Crack potentials at day 163 of the land wall half of the chamber monolith model

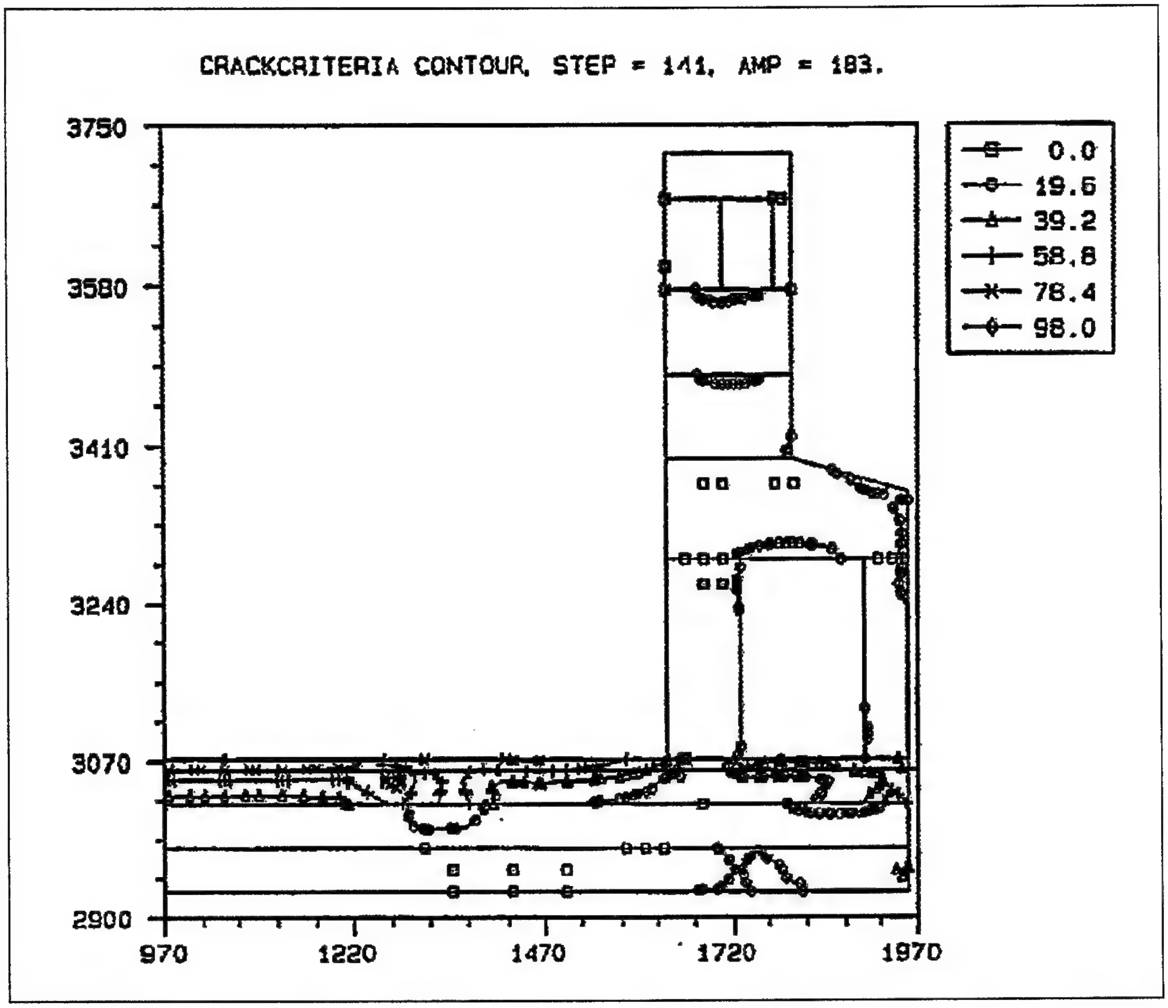

Figure B-18. Crack potentials at day 183 of the land wall half of the chamber monolith model

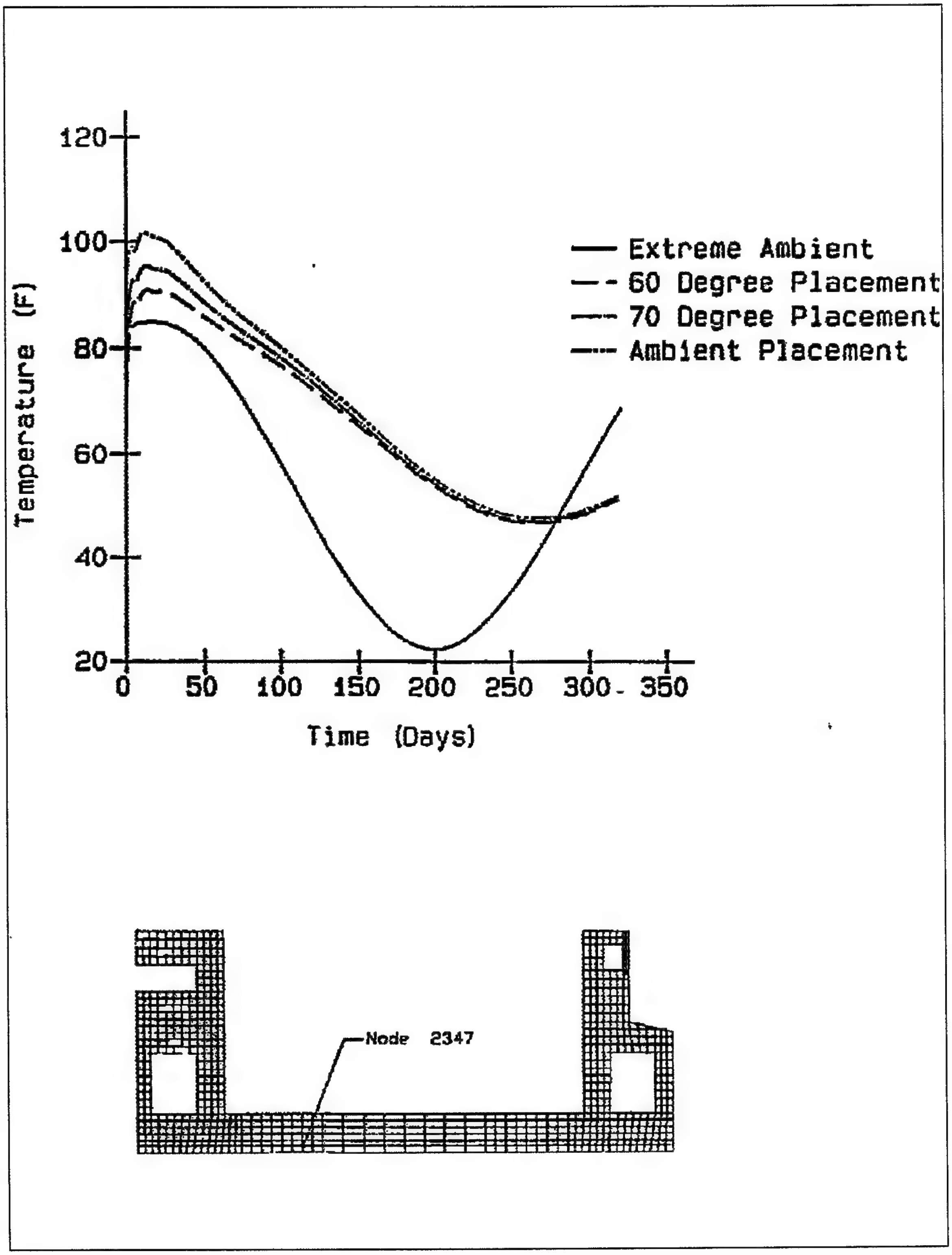

Figure B-19. Temperature time history at node 2347 of the chamber monolith model

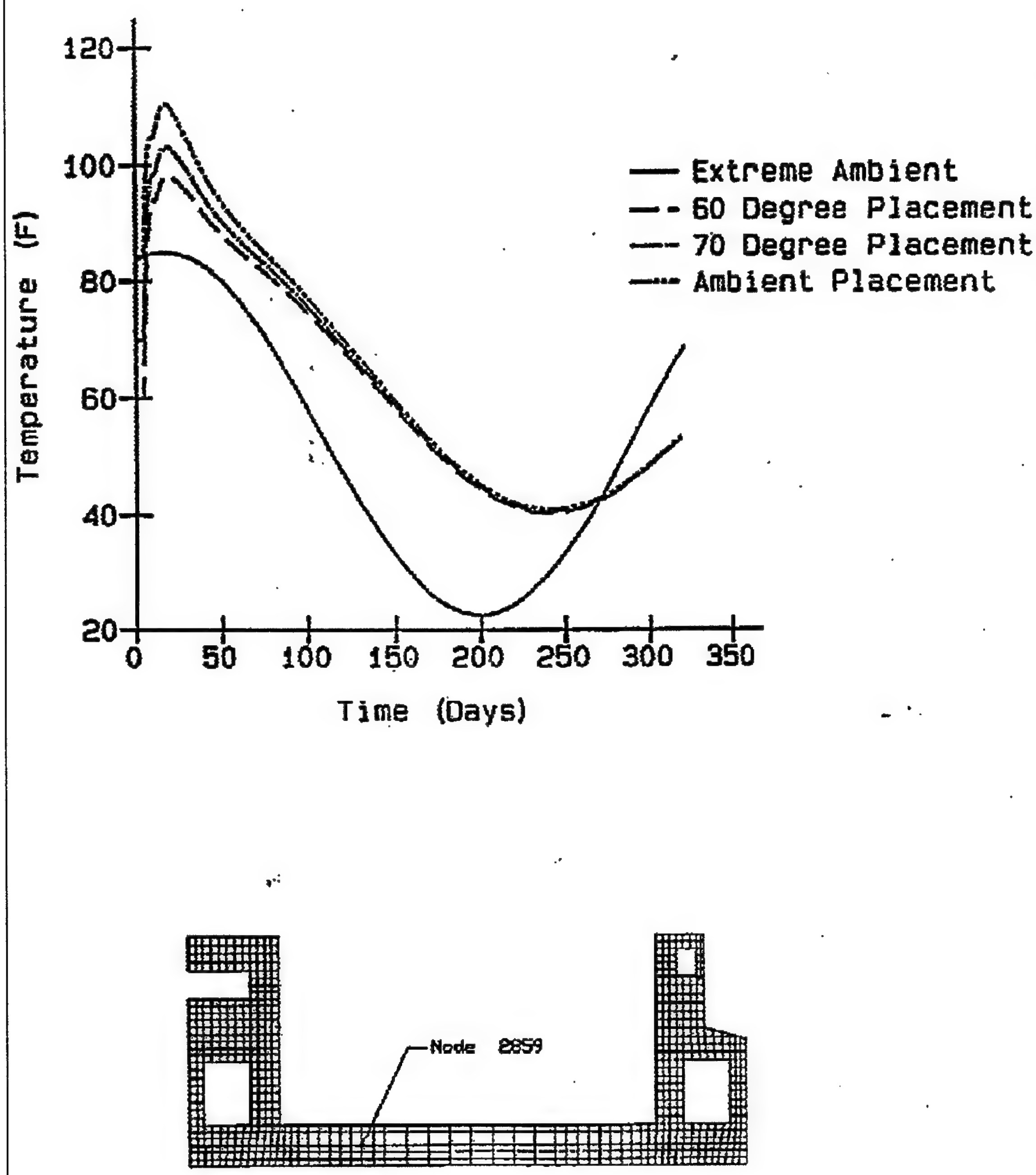

Figure B-20. Temperature time history at node 2859 of the chamber monolith model

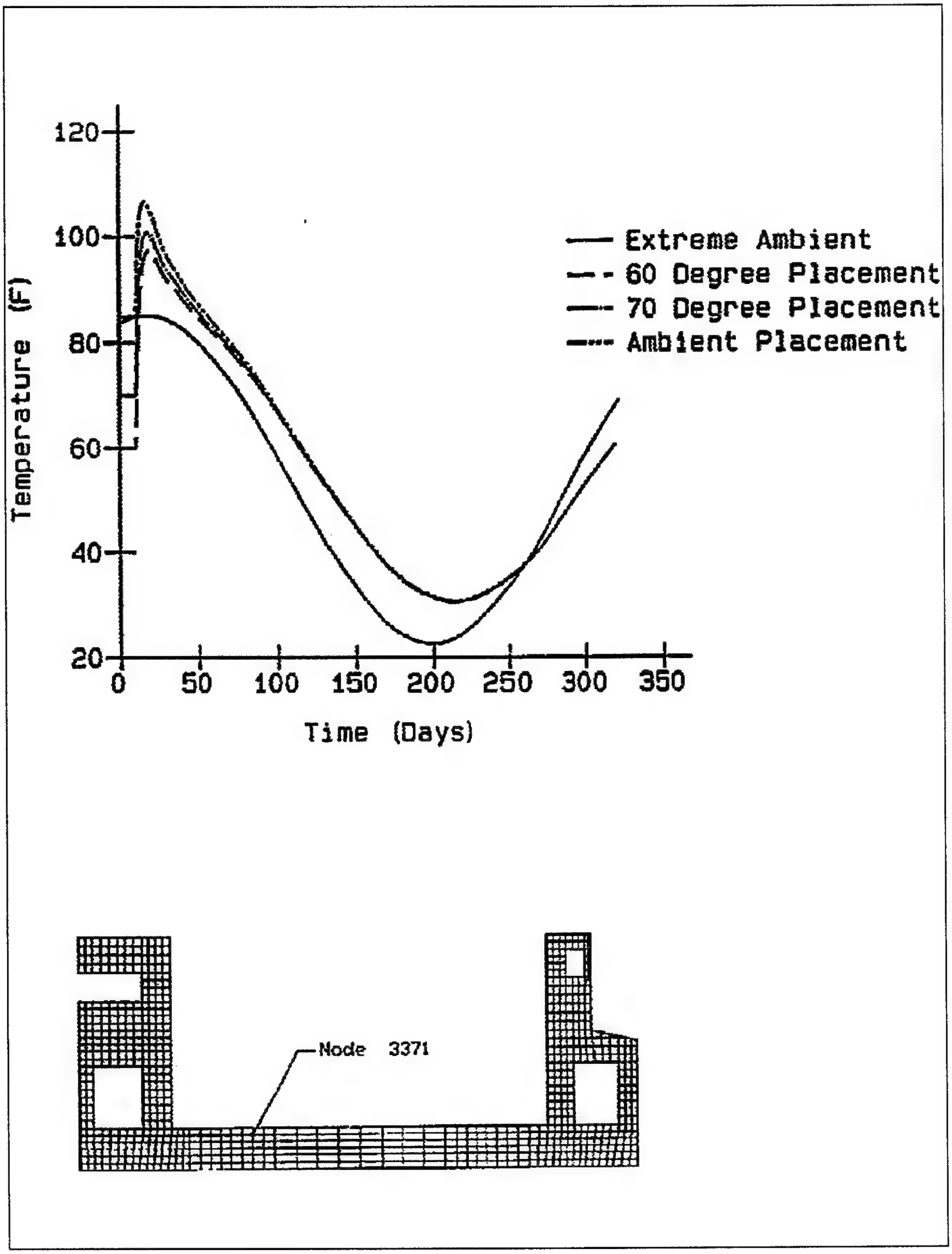

Figure B-21. Temperature time history at node 3371 of the chamber monolith model

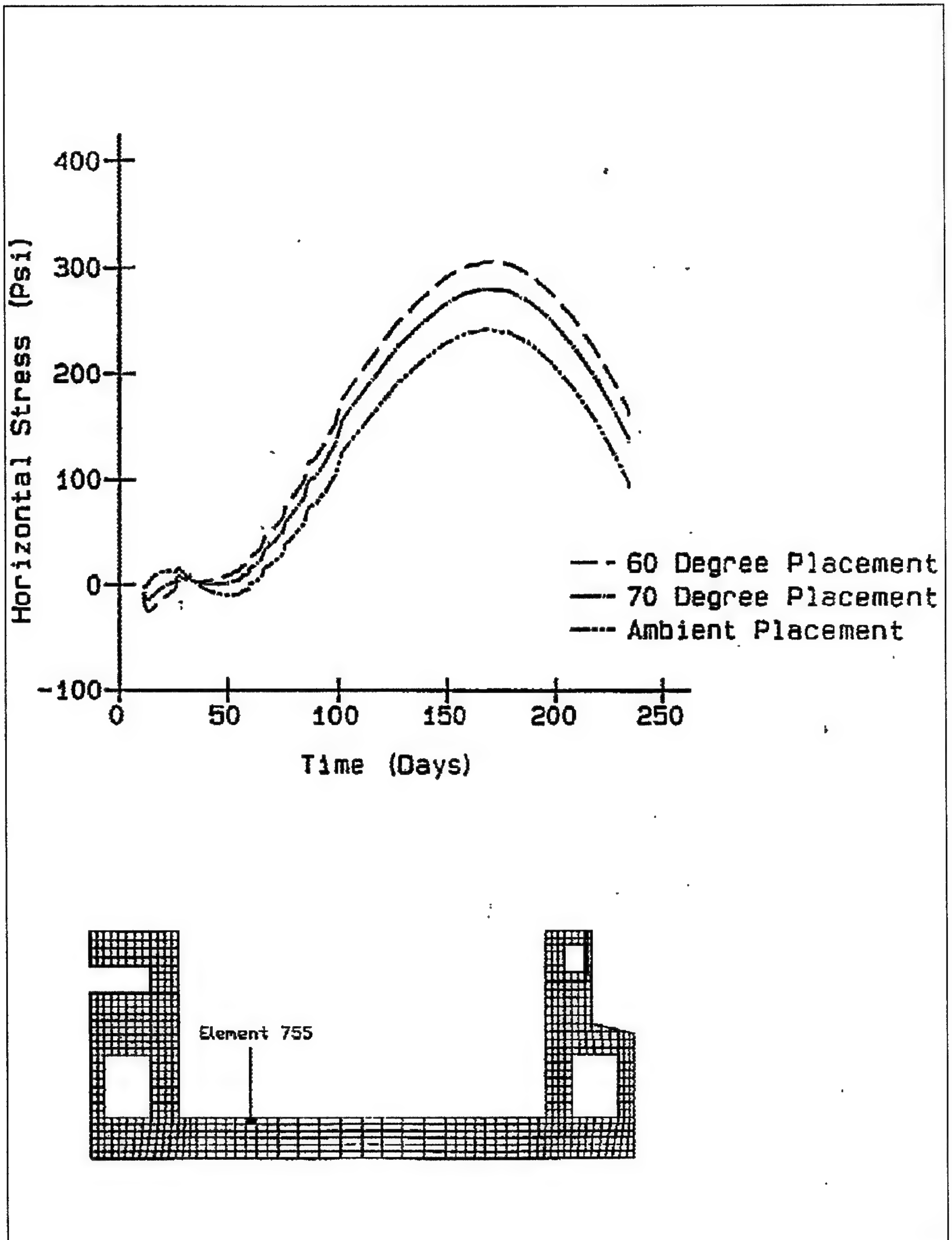

Figure B-22. Horizontal stress time history at integration point 4 of element 755 of the chamber monolith model

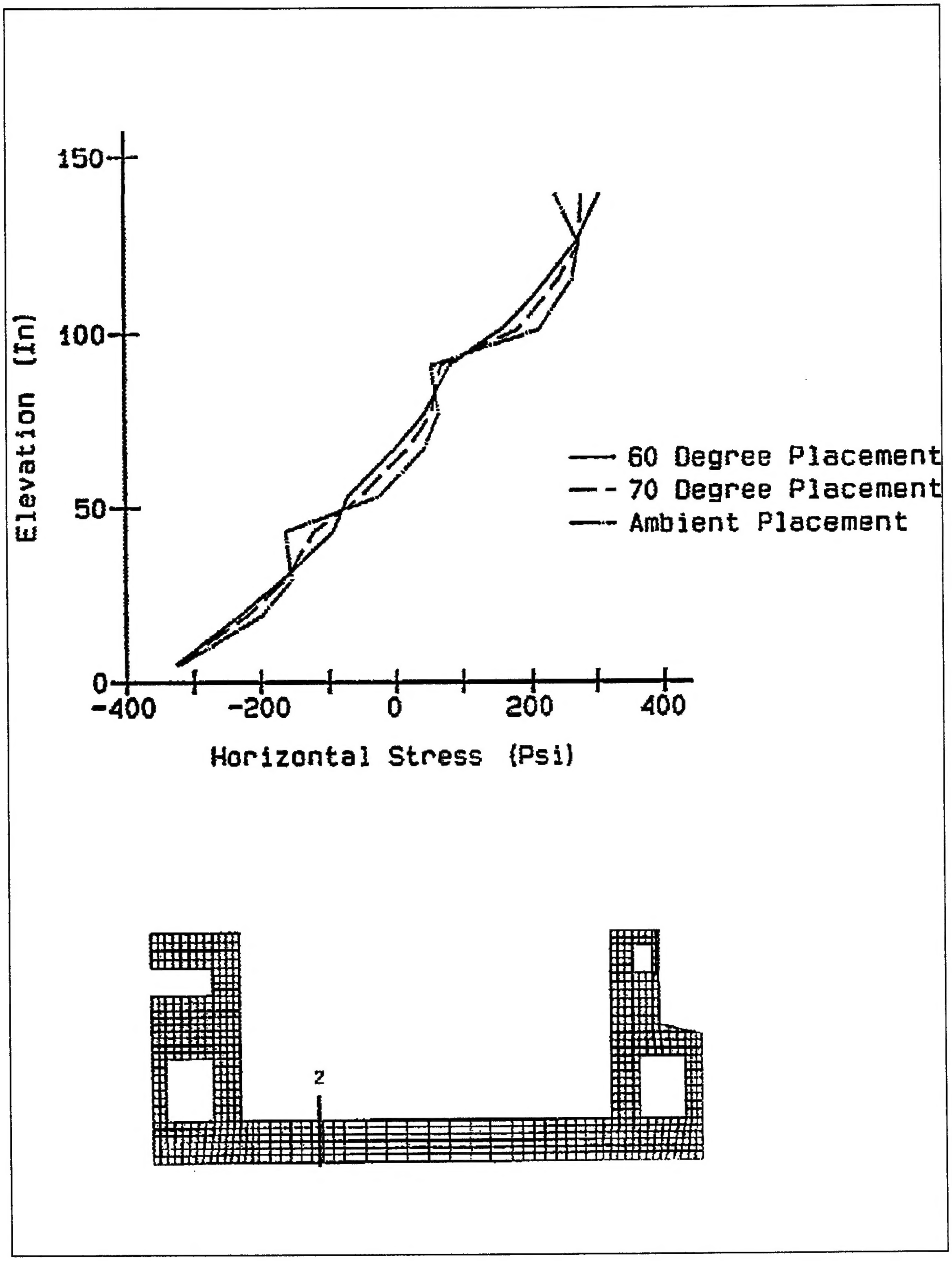

Figure B-23. Stress distribution of horizontal stress through the slab at day 177.5

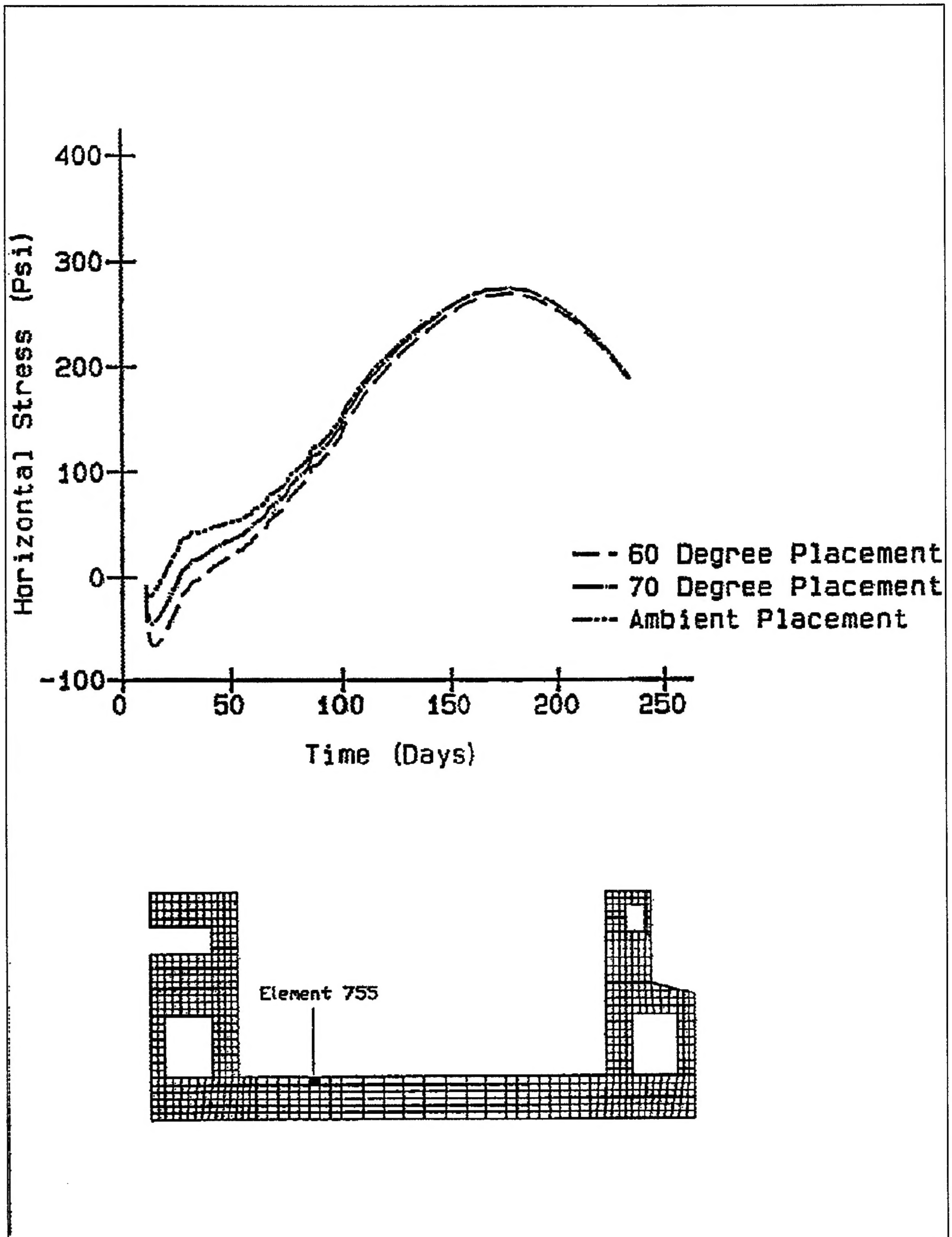

Figure B-24. Horizontal stress time history at integration point 2 of element 755 of the chamber monolith model

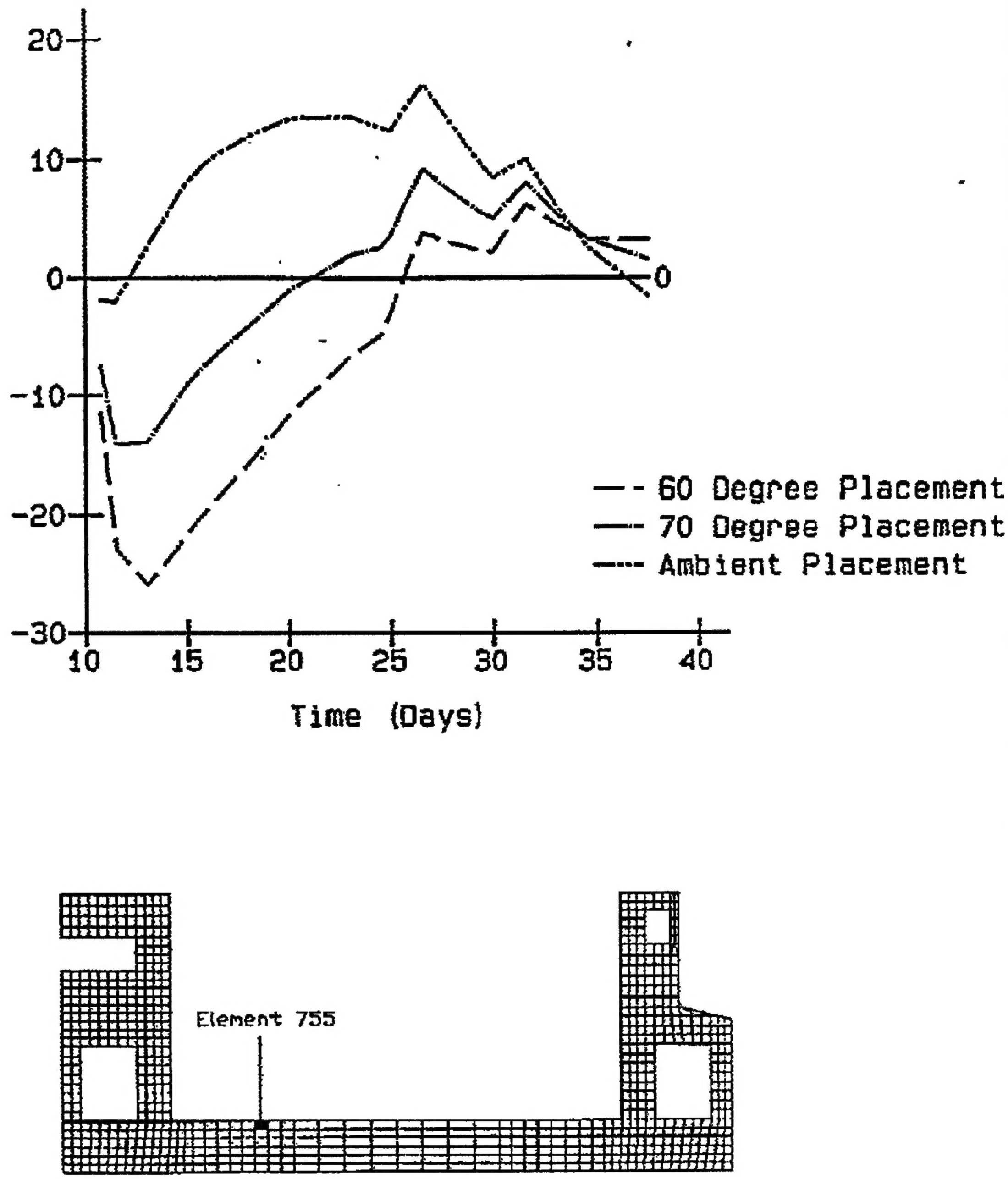

Figure B-25. Horizontal stress time history for the first 40 days at integration point 4 of element 755

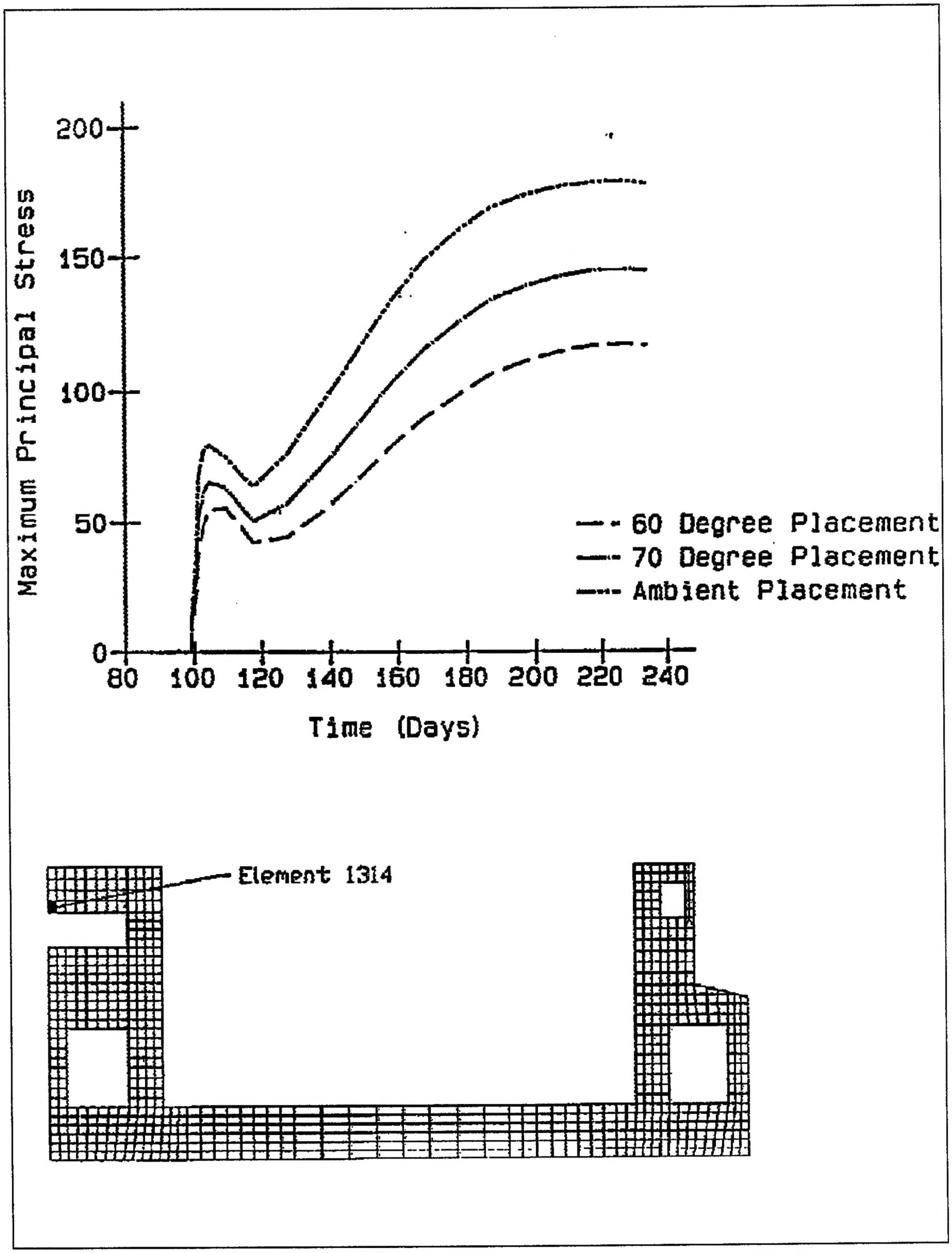

Figure B-26. Maximum principal stress time history at integration point 3 of element 1314 of the chamber monolith model